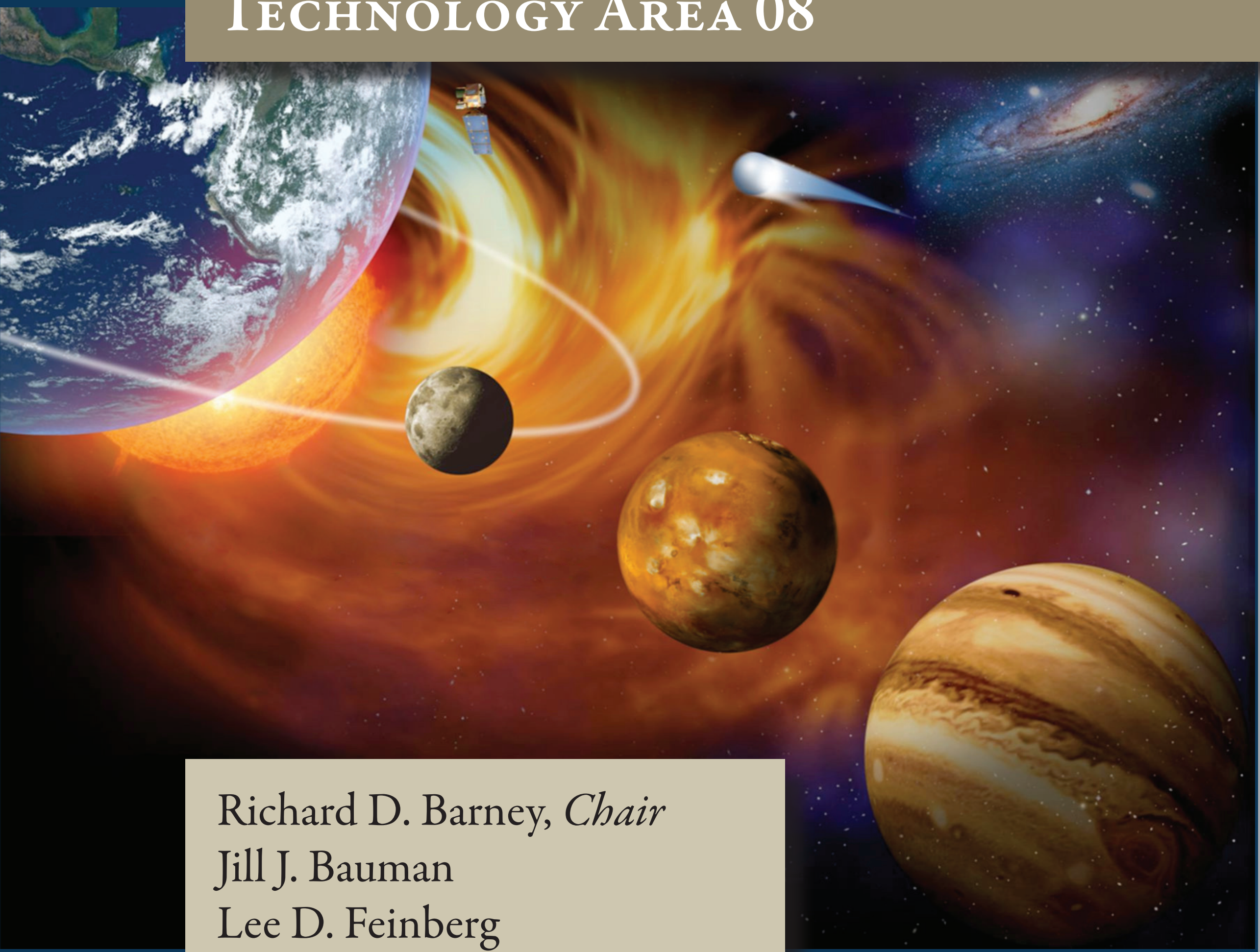
National Aeronautics and Space Administration

DRAFT Science Instruments, Observatories, and Sensor Systems Roadmap

Technology Area 08



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 08 input: Science Instruments, Observatories, and Sensor Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

The Science Instruments, Observatories, and Sensor Systems (SIOSS) Technology Area Roadmap leverages roadmapping activities from the 2005 NASA Advanced Planning and Integration Office (APIO) roadmap assessments: *Advanced Telescopes and Observatories and Science Instruments and Sensors*. The SIOSS technology needs and challenges identified in this document are traceable to either specific NASA science missions planned by the Science Mission Directorate ('pull technology') or emerging measurement techniques necessary to enable new scientific discovery ('push technology').

The SIOSS Team employed a multi-step process to generate the roadmaps. The first step was to review existing governing documents (such as Decadal Surveys, roadmaps, and science plans) for each of the four NASA Science Mission Divisions (SMD): Astrophysics, Earth Science, Heliophysics, and Planetary. From these documents, specific technology needs were identified that enable planned and potential future missions. Detailed lists of these technology needs for each SMD division were tabulated and then reviewed and refined by individual mission and technology-development stakeholders.

The second step involved consolidating the technology needs for each mission into broad categories for analysis. For example, many missions across all divisions require new or improved detector technology. These broad categories were then organized into a Technology Area Breakdown Structure (TABS) (Figure 1). A three-tier TABS structure was used to organize diverse technologies covering Remote Sensing Instruments/Sensors, Observatories, and In-situ Instruments/Sensors. **Remote Sensing Instruments/Sensors** includes components, sensors, and instruments sensitive to electromagnetic radiation including photons, as well as any other particles, electromagnetic fields, both DC and AC, acoustic energy, seismic energy, or whatever physical phenomenology the science requires. **Observatory** includes technologies that collect, concentrate, and/or transmit photons. **In-situ Instruments/Sensors** includes components, sensors, and instruments sensitive to fields, waves, particles that are able to perform in-situ characterization of planetary samples.

The final roadmapping step focused on identifying technologies that may not be directly linked to SMD missions that show the potential for radical improvement in measurement capabilities. A push technology questionnaire was developed by the SIOSS Team and sent to Chief Technologists at all NASA centers as well as to several members of the NASA scientific community. As a result of this feedback, we considered many new technologies and measurement techniques.

The following tables/roadmaps are included in the SIOSS report:

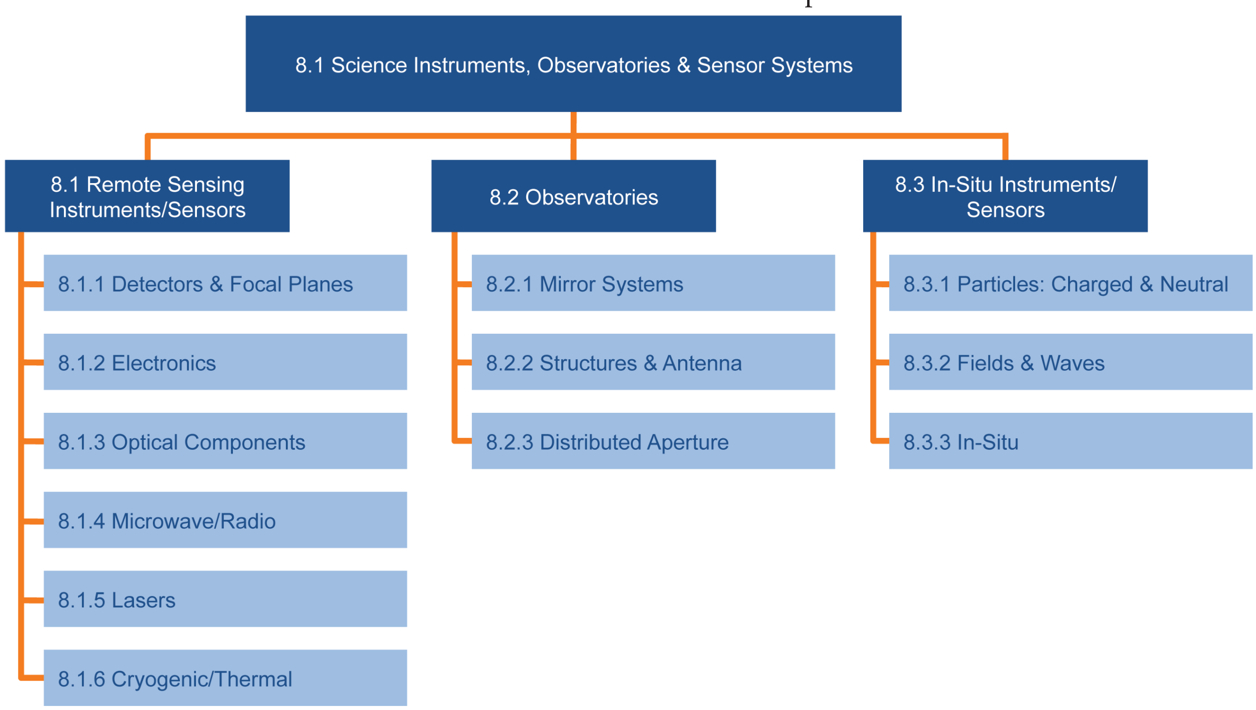


Figure 1. *Technology Area Breakdown Structure*

- SIOSS Technology Area Strategic Roadmap
- Top Technologies Table
- Technology Area Breakdown Structure
- Astrophysics, Earth Science, Heliophysics, and Planetary Technology Needs Tables
- Remote Sensing Instruments/Sensors Technologies Challenges Table and Roadmap
- Observatory Technologies Challenges Table and Roadmap
- In-situ Instruments/Sensors Technology Challenges Table and Roadmap
- Push Technologies and Measurement Techniques Summary Tables
- Interdependencies between SIOSS Technology and other Technology Assessment Areas

The roadmaps for Remote Sensing Instruments/Sensors (8.1), Observatory (8.2), and In-Situ Instruments/Sensors (8.3) were merged into an overall Technology Area Strategic Roadmap (TASR) required by the Office of the Chief Technologist and shown in Figure 2. This summary roadmap includes multiple technologies linked to similar missions and includes references to key performance targets for both push and pull technologies. It is not meant to establish investment priorities.

The Science Instruments, Observatories, and Sensor systems' top technical challenges table summarizes generic classes of near-, mid- and long-term investments in SIOSS technologies that would enhance or enable a wide range of potential science missions. Investments in the maturation of SIOSS technologies needs to be balanced between the shorter- and longer-term needs, as many of the 2017-2022 and beyond technologies can take longer to develop. For each area, the challenge is to advance the state of the art in the Technology Categories shown below by at least 2X to 10X and, in the case of long-term needs, to develop entirely new revolutionary capabilities. The Top Technical Categories are not in any priority order; rather the list is organized by general need within selected timeframes.

Top Technology Categories

Present to 2016

- In-situ Sensors for Planetary Sample Return/Analysis
- Advanced Microwave Components and Systems
- High Efficiency Coolers
- Large Focal Plane Arrays
- High Efficiency Lasers
- Low-Cost, Large-Aperture Precision Mirrors
- In-situ Particle, Field and Wave Sensors
- Radiation-Hardened Instrument Components

2017-2022

- High-Contrast Exoplanet Technologies
- Ultra-Stable Large Aperture UV/O Telescopes
- Quantum Optical Interferometry (Atomic Interferometers)
- Spectrometers for Mineralogy
- Sample Handling
- Extreme Environment Technologies

2023 and Beyond

- Surface Chronology
- Particle and Field Detectors
- Advanced spatial interferometric imaging

While the SIOSS roadmap concentrates primarily on SMD applications (astrophysics, Earth, heliophysics and planetary science), SIOSS technology is broadly applicable to the entirety of NASA missions. Section 3 and Table 9 details how SIOSS technology can enable and enhance applications related to many other NASA mission directorates.

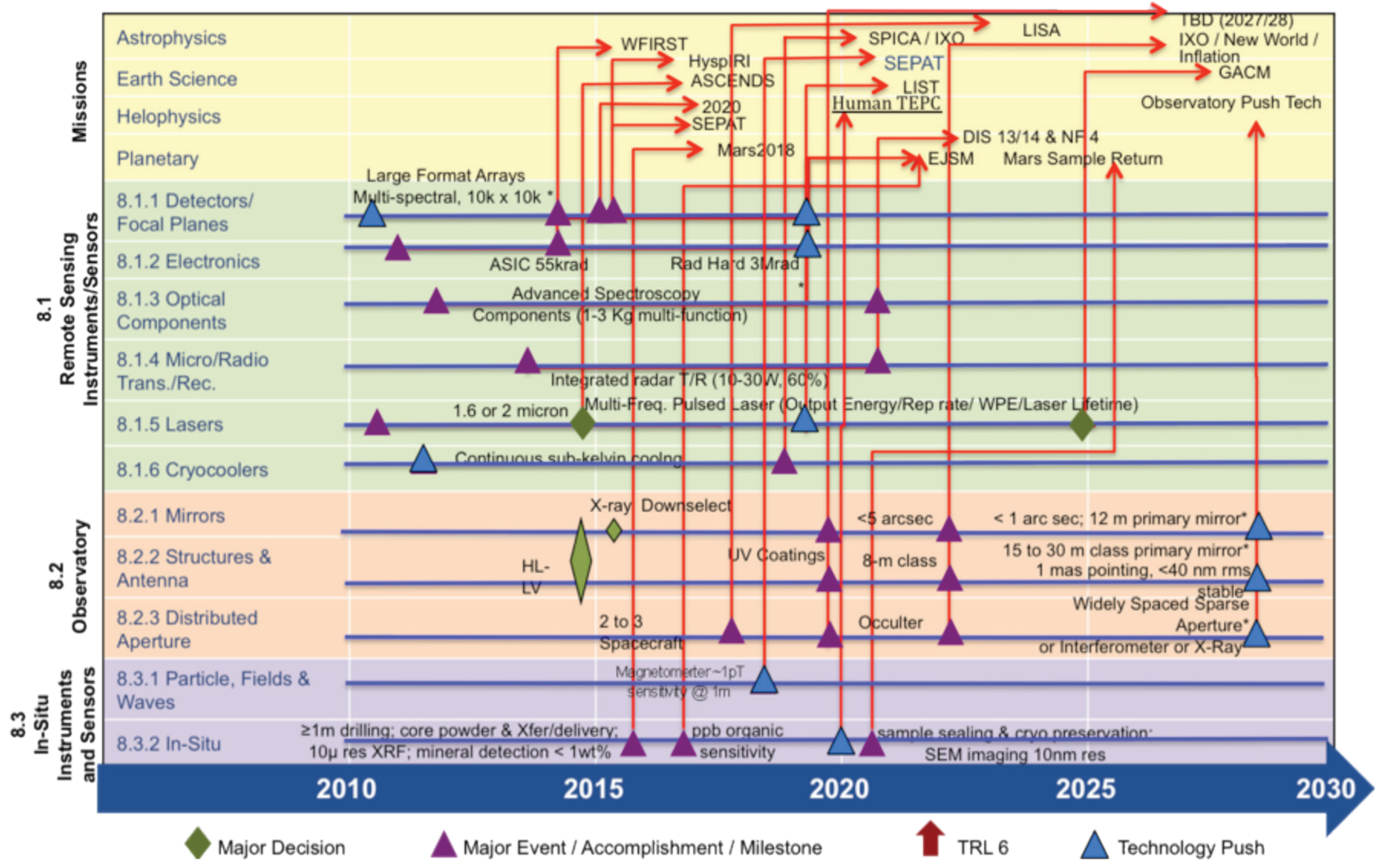
1. GENERAL OVERVIEW

1.1. Technical Approach

The Science Instruments, Observatories, and Sensor Systems (SIOSS) Technology Area Roadmap leverages roadmapping activities from the 2005 NASA Advanced Planning and Integration Office (APIO) roadmap assessments: Advanced Telescopes and Observatories and Science Instruments and Sensors. The SIOSS technology needs and challenges identified in this document are traceable to either specific NASA science missions planned by the Science Mission Directorate ('pull technology') or emerging measurement techniques necessary to enable new scientific discovery ('push technology').

The SIOSS Team employed a multi-step process to generate the roadmaps. The first step was to review existing governing documents (such as Decadal Surveys, roadmaps, and the science plans) for each of the four NASA Science Mission Divisions (SMD): Astrophysics, Earth Science, Heliophysics, and Planetary. From these documents, specific technology needs were identified that enable planned and potential future missions. Detailed lists of these technology needs for each SMD division were tabulated and then reviewed

Figure 2: *SIOSS #8 Technology Area Strategic Roadmap*



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and refined by individual mission and technology-development stakeholders. The second step involved consolidating the technology needs for each mission into broad categories for analysis. These broad categories were then organized into a Technology Area Breakdown Structure (TABS). A three-tier TABS structure was used to organize diverse technologies covering Remote Sensing Instruments/Sensors, Observatories, and In-situ Instruments/Sensors.

Remote Sensing Instruments/Sensors includes components, sensors, and instruments sensitive to electromagnetic radiation including photons, as well as any other particles (charged, neutral, dust), electromagnetic fields, both DC and AC, acoustic energy, seismic energy, or whatever physical phenomenology the science requires. **Observatory** includes technologies that collect, concentrate, and/or transmit photons. **In-situ Instruments/Sensors** includes components, sensors, and instruments sensitive to fields, waves, and particles and able to perform in-situ characterization of planetary samples.

The final roadmapping step focused on identifying "push" technologies that show promise of radically improving measurement capabilities that enable emerging missions. A push technology questionnaire was developed by the SIOSS Team and sent to Chief Technologists at all NASA centers as well as to several members of the NASA scientific community. As a result of this feedback, we considered many new technologies and measurement techniques not directly linked to NASA missions.

1.2. Benefits

NASA's pursuit of science and exploration cannot proceed without the development of new remote- sensing instruments/sensors, observatories, and sensor technologies. These technologies are necessary to collect and process scientific data, either to answer compelling science questions as old as humankind (e.g., how does life begin?) or to provide crucial knowledge to enable robotic missions (e.g., remote surveys of Martian geology to identify optimal landing sites). Several of these technologies are also required to support human missions. In particular, they are needed to determine the safety of the environment and its suitability for human operations. Section 3.0 details linkages with other TAs.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

The SIOSS technology needs and challenges identified in this document are directly traceable to either specific NASA science missions planned by the Science Mission Directorate ('pull technology') or emerging measurement techniques necessary to enable new scientific discovery ('push technology').

The set of top-level strategic documents listed below were used to prepare the SIOSS roadmaps. These sources included a variety of planning documents that articulate NASA and research community priority objectives. Additionally, a comprehensive design reference mission set was compiled from the specific reference documents, with emphasis on the *2010 NASA Science Plan and Agency Mission Planning Manifest* (4/2010).

Specific reference documents include:

- *Advanced Telescopes and Observatories*, APIO, 2005
- *Science Instruments and Sensors Capability*, APIO, 2005
- *New Worlds, New Horizons in Astronomy and Astrophysics*, NRC Decadal Survey, 2010
- *Panel Reports — New Worlds, New Horizons in Astronomy and Astrophysics*, NRC Decadal Survey, 2010
- *Heliophysics, The Solar and Space Physics of a New ERA, Heliophysics Roadmap Team Report to the NASA Advisory Council*, 2009
- *Earth Science and Applications from Space*, NRC Decadal Survey, 2007
- *New Frontiers in the Solar Systems*, NRC Planetary Decadal Survey, 2003
- *The Sun to the Earth — and Beyond*, NRC Heliophysics Decadal Survey, 2003
- *2010 Science Plan*, NASA Science Mission Directorate, 2010
- *Technology Development Project Plan for the Advanced Technology Large Aperture Space Telescope (ATLAST)*, NASA Astrophysics Mission Concept Study, 2009
- *Agency Mission Planning Manifest*, 2010
- *Launching Science: Science Opportunities provided by NASA's Constellation System*, report of National Research Council's Space Studies Board, National Academy Press, 2008.

1.4. Top Technical Challenges

Table 1 summaries the top technical challenges identified for SIOSS. Near- and mid-term challenges represent required improvements in the state of the art of at least 2X and, in many cases, an order of magnitude (10X) improvement goal.

Table 1. *Summary of SIOSS Top Near-, Mid- and Far-Term Technology Challenges (2X to 10X Improvements in the State of the Art & New Revolutionary Capabilities)*

Present to 2016 (Near Term)
In-situ Sensors for Planetary Sample Returns and In-Situ Analysis Integrated/miniaturized sensor suites to reduce volume, mass & power; Sub-surface sample gathering to >1 m, intact cores of 10 cm, selective sub-sampling all while preserving potential biological and chemical sample integrity; Unconsolidate material handling in microgravity; Temperature control of frozen samples.
Low-Cost, Large-Aperture Precision Mirrors UV and optical lightweight mirrors, 5 to 10 nm rms, <$2M/m^2$, <$30kg/m^2$ X-ray: <5 arc second resolution, < $0.1M/m^2$ (surface normal space), <3 kg/m^2
High-Efficiency Lasers High power, multi-beam/multi-wavelength, pulsed and continuous wave 0.3-2.0 μm lasers; High efficiency, higher rep rate, longer life lasers.
Advanced Microwave Components and Systems Low-noise amplifiers > 600 GHz, reliable low-power high-speed digital & mixed-signal processing electronics; RFI mitigation for >40 GHz; low-cost scalable radiometer; large (D/lambda>8000) deployable antennas; lower-mass receiver, intermediate frequency signal processors, and high-spectral resolution microwave spectrometers.
High-Efficiency Coolers Continuous sub-Kelvin (100% duty cycle) with low vibration, low power (<60W), low cost, low mass, long life
In-situ Particle, Field and Wave Sensors Integrated/Miniaturized sensor suites to reduce volume, mass and power; Improved measurement sensitivity, dynamic range and noise reduction; Radiation hardening; Gravity wave sensor: 5μcy/√Hz, 1-100mHz
Large Focal-Plane Arrays For all wavelengths (X-Ray, FUV, UV, Visible, NIR, IR, Far-IR), required focal planes with higher QE, lower noise, higher resolution, better uniformity, low power and cost, and 2X to 4X the current pixel counts.
Radiation-Hardened Instrument Components Electronics, detectors, miniaturized instruments; low-noise low-power readout integrated circuits (ROIC); radiation-hardened and miniaturized high-voltage power supplies
2017 to 2022 (Mid Term)
High-Contrast Exoplanet Technologies High-contrast nulling and coronagraphy ($1x10^{-10}$, broadband); occulters (30 to 100 meters, < 0.1 mm rms)
Ultra-Stable Large Aperture UV/O Telescopes > 50 m^2 aperture, < 10 nm rms surface, < 1 mas pointing, < 15 nm rms stability, < $2M/m^2$
Atomic Interferometers Order-of-magnitude improvement in gravity-sensing sensitivity and bandwidths Science and navigation applications
2023 and Beyond (Long Term)
Sample Handling and Extreme Environment Technologies Robust, environmentally tolerant robotics, electronics, optics for gathering and processing samples in vacuum, microgravity, radioactive, high or low temperature, high pressure, caustic or corrosive, etc. environments.
Spectrometers for Mineralogy Integrated/miniaturized planetary spectrometers to reduce volume, mass and power.
Advanced Spatial Interferometric Imaging Wide field imaging & nulling to spectroscopically image an Earth-twin with >32x32 pixels at 20 parsecs.
Many Spacecraft in Formation Alignment & positioning of 20 to 50 spacecraft distributed over 10s (to 1000s) of kilometers to nanometer precision with milli-arc second pointing knowledge and stability
Particle and Field Detectors Order-of-magnitude increase in sensitivity

The long-term challenges are new revolutionary capabilities that would enable entirely new missions. Given the wide array of SIOSS science instruments, sensors, and observatories, it is difficult to limit the discussion to just 10 top technical challenges. Nearly every scientific application has unique requirements. Therefore, the challenges outlined in Table 1 represent broad areas. Moreover, there is no way to prioritize these top technical challenges other than to group them into general-need timeframes. Therefore, this is not a priority ordering.

Finally, it is not the function of this assessment to recommend investments in any specific technology. A healthy technology R&D program requires three elements: competition, funding, and peer review. Competition is the fastest, most economical way to advance the state of the art and peer review is necessary to determine which technologies should be funded.

2. DETAILED PORTFOLIO DISCUSSION

2.1. Summary Description

A three-tier TABS structure (see Figure 1) was used to organize diverse technologies, including Remote Sensing Instruments/Sensors, Observatories, and In-situ Instruments/Sensors.

Remote Sensing Instruments/Sensors includes components, sensors, and instruments sensitive to electromagnetic radiation including photons, as well as any other particles, electromagnetic fields, both DC and AC, acoustic energy, seismic energy, or whatever physical phenomenology the science requires. **Observatory** includes technologies that collect, concentrate, and/or transmit photons. In-situ **Instruments/Sensors** includes components, sensors, and instruments sensitive to fields, waves, particles that are able to perform in-situ characterization of planetary samples.

2.2. Technology Needs

As summarized by SMD's 2010 Science Plan, strategic science missions are selected, often by competitive process, to answer "profound questions that touch us all." They are defined by NRC Decadal Surveys and are consistent with U.S. national space policy. SMD organizes its science portfolio along four themes: Astrophysics, Earth Science, Heliophysics, and Planetary Science. Given the availability of guidance documents (such as decadal reports), SIOSS created comprehensive lists of technology needed to enable or enhance planned and potential future missions. These lists were reviewed and refined by individual mission and technology-development stakeholders and then deconstructed and consolidated according to the TABS of Section 2.1. They then were analyzed and grouped into technology-development challenges for push as well as pull technologies. Each TABS second-level technology section contains a separate "push" technology table that was compiled from NASA center inputs.

2.2.1. Science Mission Directorate Technology Needs

2.2.1.1. Astrophysics Technology Needs

The National Academy 2010 Decadal Report, *New Worlds, New Horizons*, has recommended a suite of missions and technology-development programs to study three compelling Astrophysics science themes: Cosmic Dawn: Searching for the First Stars, Galaxies and Black Holes; New Worlds: Seeking Nearby, Habitable Planets; Physics of the Universe: Understanding Scientific Principles. The specific missions, with their potential launch dates (which drive TRL6 need dates) and development programs, are:

- Wide Field Infrared Survey Telescope (WFIRST), 2018
- Explorer Program, 2019/2023
- Laser Interferometer Space Antenna (LISA), 2024
- International X-ray Observatory (IXO), mid/late 2020s
- New Worlds Technology Development Program, mid/late 2020s
- Epoch of Inflation Technology Development Program, mid/late 2020s
- U.S. Contribution to the JAXA-ESA SPICA Mission, 2017
- UV-Optical Space Capability Technology Development Program, mid/late 2020s
- TRL 3-to-5 Intermediate Technology Development Program

All can be enhanced or enabled by technology development to reduce cost, schedule, and performance risks. The Decadal Survey made several recommendations, including technology funding for: 1) Future missions at a level of ~10% of NASA's anticipated budget for each mission to reduce risk and cost; 2) *New Worlds, Inflation Probe and Future UV-Optical Space Capability Definition* Technology Programs to prepare for missions beyond 2020; and 3) "General" technology to define, mature, and select approaches for future competed missions, and 4) "Blue sky" technology to provide transformational improvements in capability and enable undreamed of missions.

Astrophysics missions require technologies from both SIOSS and other technology-assessment areas. For SIOSS, Astrophysics needs map into TABS 8.1, Remote Sensing Instruments/Sensors, and 8.2, Observatory Technology (Table 2). The LISA mission requires inertial gravity-wave sensor technology, which is in 8.3, In-situ Instruments/Sensors. Aside from near-term, mission-specific technology already under development, Astrophysics requires additional advancements in five generic technology areas:

- Detectors and electronics for X-ray and UV/optical/infrared (UVOIR);
- Optical components and systems for starlight suppression, wavefront control, and enhanced UVOIR performance;
- Low-power sub 10K cryo-coolers;
- Large X-ray and UVOIR mirror systems; and
- Multi-spacecraft formation flying, navigation, and control.

Additionally, potential Astrophysics missions depend upon several non-SIOSS technologies, including:

- Affordable volume and mass capacities of launch vehicles to enable large-aperture observatories and mid-capacity missions;
- Terabit communication; and
- Precision pointing and formation-flying navigation control (i.e. micro-Newton thrusters, etc.).

2.2.1.2. Earth Science Technology Needs

The National Academy 2007 Decadal Report, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, recommended a suite of missions and technology- development programs to study compelling Earth Science themes: Weather, Solid Surface and Interior; Carbon Cycle and Ecosystems; Water and Energy Cycles; Climate Variability and Change; and Atmospheric Composition. They are arranged in tiers based on estimated cost, science priority (as determined by the NRC), societal benefits, and degree of technology readiness.

Tier 1

- Tier 1 missions are currently under development and thus the project management is unlikely to be able to introduce significant new technology or risk at this phase of the mission lifecycle

Table 2. *Summary of Astrophysics Technology Needs*

Mission	Technology	Metric	State of Art	Need	Start	TRL6
UVOTP Push	Detector arrays: Low noise	Pixel QE UV QE Visible Rad Hard	2k x 2k	4k x 4k > 0.5 90-300 nm > 0.8 300-900 nm 50 to 200 kRad	2012	2020
NWTP Push	Photon counting arrays	Pixel array visible Visible QE	512 x 512, 80% 450-750 nm	512x512 >80% 450-900 nm	2011	2020
SPICA ITP Push	Far-IR detector arrays	Sens. (NEP W/√Hz Wavelength Pixels	1e-18 > 250µm 256	3e-20 35-430µm 1k x 1k	2011	2015 2020
IXO Push	X-ray detectors (Micro-calorimeter / Active pixel sensor)	Pixel array Pixel size Energy res @ 6keV Noise QE Count rate/pixel Frame rate	6x6/64x64 300 µm 4 eV 10-15 e- RMS 300 cts/s 100 kHz@2e-	40 x 40/1kx1k 100 µm 2 eV 2-4 e- RMS >0.7 0.3-8 keV 1000 cts/s 0.5 - 1 MHz@2e	2011	2015
WFIRST IXO	Detector ASIC	Speed @ low noise Rad tolerance	100 kHz 14 krad	0.5 - 1 MHz 55 krad	2011	2013
NWTP	Visible Starlight suppression: coronagraph or occulter	Contrast, Contrast stability Passband, Inner Working Angle	$> 1 \times 10^{-9}$ --- 10%, 760-840 nm 4 λ/D	< 1 x 10-10 1 x 10-11/image 20%, at V, I, and R 2λ/D – 3λ/D	2011	2016
NWTP	Mid-IR Starlight suppres: interferometer	Contrast, Passband mid-IR	1.65×10^{-8}, laser, 30% at 10 µm	$< 1 \times 10^{-7}$, broadband > 50% 8µm	2011	2020
NWTP UVOTP	Active WFSC; Deformable Mirrors	Sensing, Control (Actuators)	λ/10,000 rms, 32 x 32	< λ/10,000 rms, 128 x 128	2011	2020
IXO	XGS CAT grating	Facet size; Throughput	3x3 mm; 5%	60x60mm; 45%	2010	2014
Various	Filters & coatings	Reflect/transmit; temp			2011	2020
Various	Spectroscopy	Spectral range/resolve			2011	2020
SPICA IXO	Continuous sub-K refrigerator	Heat lift Duty cycle	< 1 µW 90 %	> 10 µW 100 %	2011	2015
IXO Push	Large X-ray mirror systems	Effective Area HPD Resolution Areal Density; Active	$0.3\ m^2$, 15 arcsec, $10\ kg/m^2$; no	$>3\ m^2$ ($50\ m^2$), <5 arcsec (<1 as), $1\ kg/m^2$; yes	2011	2020 (30)
UVOTP Push	Large UVOIR mirror systems	Aperture diameter, Figure Stability, Reflectivity kg/m^2, $\$/m^2$	2.4 m, < 10 nm, rms, ---, >60%, 120-900 nm, $30\ kg/m^2$ $\$12M/m^2$	3 to 8 m (15 to 30 m) <10 nm rms >9,000 min >60%, 90-1100 nm Depends on LV $<\$1M/m^2$	2011	2020 (30)
WFIRST	Passive stable structure	Thermal stability	Chandra	WFOV PSF Stable	2011	2014
NWTP	Large structure: occulter	Dia; Petal Edge Tol	Not demonstrated	30-80 m; <0.1mm rms	2011	2016
NWTP UVOTP Push	Large, stable telescope structures (Passive or active)	Aperture diameter Thermal/dynamic WFE Line-of-sight jitter kg/m^2 $\$/m^2$	6.5 m 60 nm rms 1.6 mas $40\ kg/m^2$ $\$4\ M/m^2$	8 m (15 to 30 m) < 0.1 nm rms 1 mas <20 (or 400) kg/m^2 $<\$2\ M/m^2$	2011	2020 (30)
LISA NWTP	Drag-Free Flying Occulter Flying	Residual accel Range Lateral alignment	$3 \times 10^{-14}\ m/s^2/\sqrt{Hz}$	$3 \times 10^{-15}\ m/s^2/\sqrt{Hz}$, 10,000 to 80,000 km, ±0.7 m wrt LOS	2011	2016
NWTP Push	Formation flying: Sparse & Interferometer	Position/pointing #; Separation	5cm/6.7arcmin 2; 2; 2 m	 5; 15–400-m	2011	2020
LISA Push	Gravity wave sensor, Atomic interferometer	Spacetime Strain Bandpass	N/A	$1 \times 10^{-21}/\sqrt{Hz}$, 0.1-100mHZ	2011	2019

Tier 2 (Near Term)

- Hyperspectral Infrared Imager (HyspIRI)
- Active Sensing of CO_2 Emissions over Nights, Days and Seasons (ASCENDS)
- Surface Water and Ocean Topography (SWOT)
- Geostationary Coastal and Air Pollution Events (GEO-CAPE)
- Aerosol-Cloud-Ecosystem (ACE)

Tier 3 (2016-2020) 3 (Far Term)

- Lidar Surface Topography (LIST)
- Precipitation and All Weather Temperature and Humidity (PATH)
- Gravity Recovery and Climate Experiment II (GRACE-II)
- Snow and Cold land Processes (SCLP)
- Global Atmospheric Composition Mission (GACM)
- Three-Dimensional Tropospheric Winds from Space-based Lidar (3-D Winds)

Earth Science Missions use combinations of active and passive remote sensing instruments/sensors to make the desired science measurements. Earth Science missions can benefit from technology maturation to reduce cost, schedule, and performance risks from SIOSS and other technology areas (Table 3). For SIOSS, Earth Science needs map primarily into TABS 8.1, Remote Sensing Instruments/Sensors, and 8.2, Observatory Technology. Aside from the near-term, mission-specific technology already under development, Earth Science requires enabling and enhancing technology primarily for microwave and optical instruments:

- Advance antennas, receivers, transmitters, signal- and data-processing electronics, and cryogenic coolers for efficiencies in mass and power for microwave instruments;
- Improve low-areal density telescopes in the 1-m range, filters and coatings; advance low noise/highly efficient detectors, and focal planes with readout integrated circuits (ROIC); complementary detector arrays, electronics, cryogenic coolers and data processing systems and passive hyperspectral/multispectral/imagers, (UV-Vis-IR-FIR) and spectrometers (0.3 to 50 μm),
- Advance lasers in 0.3-2.0 μm range (high power, multi-beam/multi-wavelength, pulsed, and continuous wave), detectors, receivers, larger collecting optics, and scanning mechanisms (including pointing and scanning at high angular resolution); improved quantum efficiency detectors, long-life, high-power laser diode arrays, and brighter/more-energetic laser sources; improved high damage threshold optics;
- Large telescope and RF antenna, which are key enablers for future climate and weather applications.

2.2.1.3. Heliophysics Technology Needs

The 2009 NASA Heliophysics Roadmap, Heliophysics: The Solar and Space Physics of A New Era, recommends a science- and technology-development roadmap for 2009-2030. The science program consists of two strategic mission lines: Solar Terrestrial Probes (STP) and Living with a Star (LWS). Additionally, the report recommends a robust Explorer Program of smaller competitively selected PI-led missions to complement the strategic mission lines. Heliophysics also funds missions under the Low-Cost Access to Space (LCAS) program. Mid- and far-term potential missions with their potential launch dates (which drive TRL6 need dates) that can benefit from technology investments are:

- Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS), LCAS, 2014
- Focusing Optics X-ray Solar Imager 3 (FOXSI-3), LCAS, 2016
- Origin of Near-Earth Plasma (ONEP), STP, 2018
- Climate Impacts of Space Radiation (CISR), LWS, 2020
- Solar Energetic Particle Acceleration and Transport (SEPAT), STP, 2021
- Dynamic Geospace Coupling (DGC), LWS, 2023
- Ion-Neutral Coupling in the Atmosphere (INCA), STP, 2025
- Heliospheric Magnetics (HMag), LWS, 2026

Currently, the National Academy is preparing a new Decadal Survey scheduled for publication in 2012. It is expected to redefine the Heliophysics mission list.

Heliophysics missions require technologies from both the SIOSS and other technology areas (Table 4). For SIOSS, Heliophysics technology needs map primarily into SIOSS TABS 8.1, Remote Sensing Instruments/Sensors Technology, and 8.3, In-Situ Instruments/Sensors Technology. Heliophysics missions require enabling and enhancing technology development to:

Table 3. *Summary of Earth Science Technology Needs*

Mission	Technology	Metric	State of Art	Need	Start	TRL6
ASCENDS	Multi-freq laser, 0.765/1.572/2.05 µm Pulsed	Output energy, Rep rate, Efficiency	25 µJ/25 µJ/30mJ 10kHz/50 Hz <2/4%	>3/3/65 mJ 10kHz/10kHz/50 Hz 3.5/7/10%	2012	2014
	1.6 µm CW laser	Power/module/efficiency	5W/7/8%	35W/1/10%	2012	2014
	1.26 µm CW laser	Power/module/efficiency	4W/1/3%	20W/1/8%	2012	2014
	1.57 µm detector	QE/gain/bandwidth		10%/300/10 MHz	2012	2015
	2 µm APD detector	QE/Bandwidth, NEP	> 55%/10 MHz, 10-11 W/Hz1/2	>55%/ >500 MHz, 10-14 W/Hz$^{1/2}$	2012	2014
SWOT	Ka-band power switch matrix	Power capacity	~ 500 W peak	2.5 kW peak, 110-165W avg.; Stable	2012	2015
	Ka-band receiver	Phase stability, isolation, Bandwidth	~ 50 mdeg, 68 dB, 80 MHz	~40 mdeg over 3min >80 dB, >200MHz	2012	2015
	Deployable-antenna structure	Boom length, Pointing stability	6.5 m, ~0.05 arsec roll	10-14 m, 0.005 arcsec roll/3min	2012	2015
HyspIRI	TIR spectrometer (8ch, 3-12 µm)	Frame rate	~ 1 Mpixels/sec	256 Mpixels/sec at 14bits; 32 kHz	2012	2016
GEO-CAPE	UV-Vis-NIR spec-trometer ROIC	Size, pixel pitch, frame rate, quantization, QE		1024x2048, <13µm, 4MHz,16bit, >60%uv	2013	2019
ACE	Damage-resistant UV laser at 355 nm	Energy, repetition rate, efficiency, lifetime	250mJ/100 Hz/5%	300 mJ, 100Hz, 10%, 3-5 Yrs	2012	2019
	CCD Array (355/ 532 nm)	QE, sampling rate		> 70%/90%, > 5MHz	2012	2019
	Multi-angle polarim-eter ROIC	High-processing speed @ low noise	~100 kpix/sec	>10 Mpix/sec, <40 electrons	2012	2019
	W-band radar de-ployable antenna	Reflector diameter, Sur-face accuracy	1.5mm rms@ 5 M	Main 5-6 m; sub4-5m <0.1 mm RMS	2013	2019
	W/Ka-band dual-freq. reflect array	# Elements		W-band: 2500, Ka-band: 900	2013	2019
LIST	Photon-counting det	QE	20% in a 4 x 4 arr	50% in a 1 x 1000 arr	2011	2018
	Laser altimeter (1µm)	Wallplug efficiency, Multi-beam array, PRF	~10%, 9@222µJ/beam	20%, 1000 @ 100µJ/ beam, 10 kHz	2012	2018
PATH	Correlator	Power level	224µW@375MHz	250 µW @ 1 GHz	2014	2020
	Low-mass, low-noise receiver	Noise level, power, mass, frequencies	500 K	400 K, < 50 mW, <150g, 60 - 183 GHz	2014	2020
GRACE-2	Accelerometer	Acceleration accuracy	1e-11 m/s/s	< 1e-12 m/s/s, 1-100s	2018	2021
SCLP	Dual-polarized multi-frequency feed array	Frequency bands, Polarization Scanning range		9.6 to 17.2 GHz, H and V for all freq, >10-20 degrees	2017	2022
GACM	Stable sub- mm scanning antenna	Size, surface accuracy, Areal density	1.8 m, 10 µm rms, 10 kg/m^2	4 m, 10 µm rms, <10kg/m^2	2015	2023
	Radiation-tolerant, digital spectrometer	Bandwidth, Efficiency, Channels	0.75 GHz, 6 W/GHz, 4000	8 GHz, <1.5 W/GHz, 8000	2018	2023
Push	UV laser at 305-308nm / 320-325nm	Efficiency, Output Energy	100mj	50mj	2012	2023
3-D Winds	Multi-freq laser - 2/1 µm pulsed	Output energy/rep rate/, WPE/laser lifetime	250/5Hz/2% at 2um	250/500 mJ/5/200Hz, 5%/12%, 500M/15B shots	2014	2024
	- 2 µm CW seed laser	Power	60 mW	100 mW	2014	2024
	Damage-resistant 355 nm pulsed laser	Output energy; pulse rep rate; WPE; life		320-32mJ/pulse; 120-1500 Hz; >5%; 3 yrs	2014	2024
	Lightweight mirrors	Diameter; areal density		> 0.7 m; <6 kg/m^2	2018	2024

Table 4. *Summary of Heliophysics Technology Needs*

Mission	Technology	Metric	State of Art	Need	Start	TRL6
DGC INCA CISR	Pointing system	Accuracy and knowledge	0.1 deg/.05 deg	0.02 deg/0.02 deg	2013	2018
DGC ONEP	Wide angle optical reflective systems, Isolate 83.4 nm from 121.6 nm	Wide FOV Aperture Spectral rejection of 121.6 and acceptance of 83.4 nm	20 deg 3 cm 1:30	30 deg 6 to 50 cm 1:3000	2011	2014
DGC ONEP INCA CISR	Spectral filters, Solar blind sensors, FUV sensors	Resolution Reflectivity in 60-200 nm Rejection QE 60-200 nm	5 nm FWHM 80% 10e-6 20%	2 nm FWHM >90% 10e-8 >50%	2011	2014
Push	Miniaturization	Mass and power	15 kg/10 W	3 kg/5 W	2013	2016
SEPAT HMag DGC	Fast, low-noise, Rad-hard O/UV detector	Pixel array, pixel rate, Read noise, rad tolerance	1kx1k, 10 MHz, 100 e-, 50 krad	2kx2k, 60 MHz 20 e-, 200 krad	2013	2016
GRIPS	70 K cryostat, with many channels	Number of channels Thermal leakage	~30 ~10 mW/ch	~5000, <1 mW/ch.	2011	2014
GRIPS	~20-m boom	Boom control, tip mass		~0.5 deg, 50 kg	2012	2014
Push	Fast electronics	Timing Dead time per event	10 ns 300 ns	~3 ns ~30 ns	2012	2014
ONEP Push	2 spacecraft, Formation flying	Alignment Aspect Separation control	None	1 arcsec 0.1 arcsec 100±0.1 m	2011	2015
Push	X-ray focusing lens	Energy range Angular resolution	~6 keV 1 arcsec	1 – 20 keV <0.1 arcsec	2011	2014
FOXSI	Hard X-ray focusing mirrors	Energy range FWHM Resolution	5 - 30 keV <10 arcsec	5 - 100 keV 5 arcsec	2011	2014
Push	X-ray polarization	Energy range Min. polarization	<10 keV 10%	Up to 50 keV 1%	2011	2014
Push	X-ray modulation grids	Finest pitch No. of pitches per grid	34 µm 16	10 µm 100	2011	2014
Push	X-ray TES micro-calorimeters	Resolution, count rate/pixel Number of pixels Pixel packing	4 eV, 300 c/s 32 x 32 150 x 150 µm	2 eV, 1,000 c/s 1000x1000 75 x 75 µm	2011	2015
Push	Solid-state X-ray detectors	Counting rate Pixel size	1000 c/s 500 µm	10,000 c/s 100 µm	2011	2014
Solar CubeSat	Deployable photon sieve	Diameter Transmission, Optical resolution	30 cm, 1 % 0.5 arcsec	2 m, > 5 % 0.1 arcsec	2012	2014
ONEP	≥ 20 m Boom	Stiffness		10^7 N m2	2012	2015
Push	UV image slicer	Number of slices Wavelength range	5, > 300 nm	20 Down to 90 nm	2012	2014
ONEP	E-field boom	Length, mass	10 m, 7 kg	20 m, 4 km	2012	2014
ONEP Various	Electrostatically clean solar array	Power loss due to cover and coating	20-25% loss; cost is $Ms	5%, $500K	2011	2013
SEPAT	Fast (0.01 s) imaging electron spectrometer	0.01 s Static 4Pi sr FOV/.01-2 keV with static energy angle analysis (SEAA)	0.5 s - Top Hat Energy-angle analyzer (not static)	0.01s/velocity distribution, SEAAs: 4Pi sr/ energy 0.01-2 keV/7% energy resolution	2011	2013
INCA	WINCS: Wind Ion-drift (temperatures), Neutral/ion Composition	1s cadence for WINCS @ 400 km altitude - 1W total power	Cross-track component of wind only @30 W for all measurements	1s cadence for Wind / IonDrift/ Temp/Comp @ 400 km altitude - 1W total power with onboard data analysis	2013	2017

- Improve UV and EUV detectors (sensitivity, solar blindness, array size, and pixel counts);
- Reduce noise and insensitivity of electronics and detectors to heat and radiation;
- Improve UV and EUV optical components (coating reflectivity and polarization uniformity, grating efficiency, and surface figure quality);
- Improve cryo-coolers for IR detectors; and
- Improve in-situ particle sensor-aperture size and composition identification.

Additionally, potential Heliophysics missions are critically dependent upon several non-SIOSS technologies, including:

- In-space propulsion (solar sails and solar electric) for reaching and maintaining orbits;
- Space power and radioisotopes for both near Sun and deep space;
- Terabit communication and data-compression technologies; and
- Affordable volume and mass capacities of launch vehicles.

2.2.1.4. Planetary Science Technology Needs

The National Academy 2003 Solar System Exploration (SSE) Decadal Survey, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, provided a list of planetary missions and identified the enabling technologies required to support those missions for the decade 2003-2013. Currently, the National Academy is preparing a new Decadal Survey planned for release in March 2011 that will recommend a suite of missions for 2013-2022. The 2011 Planetary Science Decadal Survey likely will make general recommendations for technology development that align with the major flight programs within the Planetary Science Division (PSD): Discovery, New Frontiers, Lunar Quest, Mars Exploration, and Outer Planets Programs. It is important to note that many Planetary Science missions and instruments are selected competitively. For missions, including their payloads, Announcements of Opportunity (AO) are released in two categories, Discovery or New Frontiers (NF). The objectives and targets of future Discovery and NF missions are known only four to six years in advance of the launch date. For these mission opportunities, as well as for strategic missions, such as those arising directly from Decadal Survey recommendations, NASA's selection of instruments is predicated on available technology or technology developments that are understood and costed in t proposals submitted by investigators in response to AOs. Consequently, development of challenging and long-lead technologies for instruments — those not realizable within the constraints of the mission life cycle — is required for likely mid-term and far-term missions. Known mission opportunities, for which advanced instruments and their associated technologies are needed, and their launch dates are:

- Discovery-13, 2018/2020
- Mars 2018, 2018
- Europa Jupiter System Mission (EJSM), early 2020
- Discovery-14, 2021/2023
- New Frontiers-4, 2024
- Mars Sample Return, mid-2020s

These missions will carry instruments that are not only capable of furthering our understanding of the Solar System, but will also characterize the surface and environments of targets for future human exploration. Planetary science instruments require technologies from both SIOSS (Table 5) and other technology areas to reduce technical, cost, schedule, and performance risk. These technologies need to support a wide range of probable target bodies (e.g. planets, moons, asteroids, comets). Table 5 presents recommendations for technology developments to enable the study of planetary objects of diverse size, shape, and rotation rate; absolute temperature and thermal variations; surface composition, topography and activity; atmospheric densities, cloud cover, gas composition, and corrosiveness; solar intensities and radiation environment; magnetic and gravitational fields; and planetary-protection measures. Future technology development of sensors, optics, electronics capable of operating in extreme environments, and sampling systems will make possible investigations of the Solar System currently thought to be impractical. These, together with investments in other technology areas, e.g. propulsion systems for sample return, will enable new missions of discovery.

2.2.2. SIOSS Technology Area Roadmaps

Each technology need identified in Section 2.2.1 is mapped to the SIOSS TABS defined in Section 2.1.

2.2.2.1. Remote Sensing Instruments/Sensors Roadmap

Remote-sensing instruments/sensors includes components, sensors, and instruments sensitive to electromagnetic radiation including photons, as

Table 5. *Summary of Planetary Science Technology Needs*

Mission	Technology	Metric	State of Art	Need	Start	TRL6
Discovery 13/14, New Frontiers 4, EJSM	Large arrays: Vis & IR	Pixel count	1 k x 1k format	>2k x 2k format	2011	2015
	Spectral-tunable IR	Narrow-band/ range	1 µm/ few µm	0.1 µm / 1-15 µm	2015	2018
	Spectral-tune Sub-mm	Tunability @ x GHz	60 @600 GHz	>150 GHz @1200	2015	2018
	γ-ray, neutron detectors	Energy resolution, Directionality	1%, 10 deg	0.1%, 1 deg	2015	2018
	Polarization	s/p, switching speed	50%, ~1 Hz	>90%, >50 Hz	2013	2018
	Photon Counting	Λ, array size	Some λ's:	UV/vis InGaAs	2010	2018
	Rad hard Detector	TID, no SEU/SEL	Heavy shielding	<100 mils shield	2010	2020
Dis 13/14, NF 4, EJSM	Rad Hard Electronics	TID tolerance	0.1-1 Mrad	3 Mrad	2010	2020
	Low Noise Electronics	Noise level (%)	<1%	<0.01%	2011	2020
	Extreme Environment Electronics	Operating temperature	-55C to 125C	-180C to125C	2011	2020
Dis 13/14, NF 4, Mars 2018, EJSM	UV to Sub-mm Filters & Optical Coatings	Transmission; Uniform Polarize; Band-pass	T~90%; U~80%; 1 nm	T>97%; U>90%; < 1nm	2012	2020
	Mini Spectrometer	Mass & Function	5-10 kg; Single	1-3 kg	2010	2020
Dis 13/14, NF 4,	Integrated radar T/R mods.	Power and efficiency	10-30 W, 40%	10-30 W, 60%	2013	2020
	Integrated radiometer receiver	Size, Frequency, Temp	100-ele; 100 GHz, Ambient Ops	Quantum-limited; 30-110 GHz; Cryo	2013	2020
Dis 13/14, NF 4, Mars 2018, EJSM	Pulsed lasers: Altimeters, LIDAR	Profiling, lifetime, sampling rate, Power	Single profiling, 6x10^8 shots, 1-40 Hz, 200-10 mJ/pulse	Multi-beams, >10^9 shots, 40-100kHz, 300-0.3mJ/pulse	2013	2020
	Pulsed lasers: Raman, LIBS	Lifetime, Sampling rate, Power	6x10^8 shots, 5 Hz, 40 mJ/pulse	>10^9 shots, >10 Hz, >200mJ/pulse	2013	2020
	CW lasers	Peak power at <250nm	10 mW	>100 mW	2013	2020
	CW tunable NIR/IR	Room temperature operation	Some λ regions	1-15 µm	2013	2020
	Diode lasers	Power at 1.083 µm	1 mW	>10 mW	2013	2020
Dis 13/14, NF 4, Mars 2018, EJSM	Particle Detectors	Energy thresholds	~10 keV, small array	~1 keV, large array	2013	2020
	Magnetometers	Sensitive, boom dist	~10 pT; 3-10 meter	~1 pT; <1 m	2013	2020
	EM Field Sensors	ADC; Coverage	8-bit; limited	18-bit; entire band	2013	2020
Dis 13/14, NF 4, Mars 2018, MSR	Gas composition	Detection; Precision	1ppmv-1ppbv;10/mil	0.01ppbv; 0.1/mil	2011	2020
	Elemental composition	Separation	0.5 wt%	0.1 wt%	2011	2020
	Mineral: APXS, IR, γ-, Raman, XRD, neutron	Detection limits	Few wt%	<1 wt%	2011	2020
	Age dating	±Myr error/Byr	±20Myr in lab	±200Myr on surface	2011	2020
	Biological	Sensitivity	Ppb	Ppt	2011	2020
	Sample handing	% cross contam	3-5%	<0.1%	2011	2020
	Instrument extreme electronics	Temperature, Radiation, g-Impact	-100 to 200 C, 300Krad-1Mrad, 20,000 g	-100 to 200 C, 300Krad-1Mrad, 20,000 g	2011	2020
	High density power	Watts	10-100 mW	0.5-1 W	2011	2020
Dis 13/14, NF 4, Mars 2018, EJSM, MSR	Sample Analysis	Volume processed	0.1-1mL aliquot	10-6 mL aliquot	2011	2020
	Organisms detection and measurement	Sensitivity	Cultivation-based, limited sensitivity	High sensitivity, detect. Breadth	2011	2014
	Sterilization	DHMR	Components	Subsystems	2011	2016
	Round trip protection	<ppb contam	Lunar	Mars	2012	2020

well as any other particles (charged, neutral, dust), electromagnetic fields, both DC and AC, acoustic energy, seismic energy, or whatever physical phenomenology the science requires. Figure 3 represents the more significant technology challenges developed from the mission needs tables in Section 2.2. Push technologies are also outlined on the roadmap below (Table 6).

Major challenges listed on the roadmap include:

- Detectors/Focal Planes: Improve sensitivity and operating temp. of single-element and large-array devices;
- Electronics: Radiation-hardened electronics with reduced volume, mass and power;
- Optics: High-throughput optics with large fields of view, high stability, spectral resolution, and uniformity at many different temperatures;
- Microwave/Radio Transmitters and Receivers: Low-noise amplifier technologies, with reliable low-power high-speed digital- and mixed-signal processing electronics and algorithms;
- Lasers: Reliable, highly stable, efficient, radiation hardened, and long lifetime (>5 years); and
- Cryogenic/Thermal Systems: Low power, lightweight, and low exported vibration.

Detector and Focal-Plane Technology: Detector and focal-plane technologies are grouped in the following categories: large-format arrays; spectrally tunable detectors; polarization sensitive detectors; photon-counting detectors; radiation-hardened detectors; and sub-Kelvin high-sensitivity detectors.

Advances in single-element and large-array detector technologies that improve sensitivity, resolution, speed and operating temperature are needed for several upcoming missions. Two major classes of X-Ray and UV/Vis/NIR/IR detectors already are required: (1) large focal-plane array (FPA) detectors with high-quantum efficiency (QE), low noise, high resolution, uniform and stable response, low power and cost, and high reliability that are suitable for survey and imaging missions; and (2) photon-counting detectors featuring ultra-low noise, high-quantum efficiency and signal gain, high-resolution and stable response, suitable for spectroscopic and planet-finding missions.

Two superconducting detector technologies show promise for high-density arrays needed for far-IR, mm-wave and x-ray astrophysics in the next decade: (1) transition-edge superconducting (TES) bolometers and microcalorimeters; and (2) microwave kinetic inductance detectors

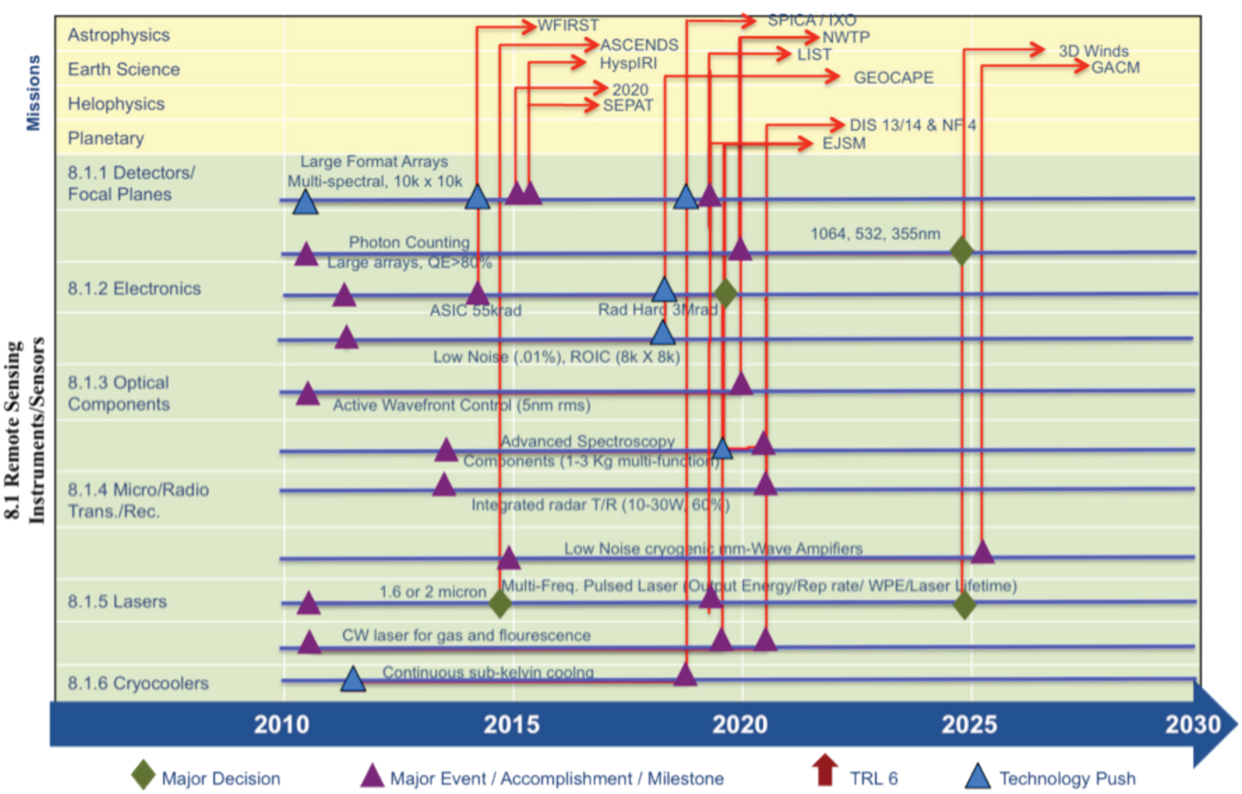

Figure 3. *SIOS Remote Sensing Instruments/Sensors Technologies Roadmap*

Push Technology	Description
8.1 Remote-Sensing Instruments/Sensors	
Quantum Optical Interferometry	Produce and measure quantum entangled-photons with lasers with the potential to improve the sensitivity of optical interferometers by multiple orders of magnitude..
Imaging Lidar	Imaging Lidar technologies involving fiber lasers and 2D detector arrays will enable “range imaging” of Earth and planetary surfaces.
Atmospheric Trace-Gas Lidar	Atmospheric trace-gas Lidar technologies for biogenic trace gas measurement and localization (Earth and Planets)
Long Range Laser Induced Mass Analysis	Long range laser induced mass analysis (LIMA) methods for atmosphere-less bodies (NEO’s, Moon, Mercury, outer planets)
Hyper-resolution Visible-NIR	Hyper-resolution Visible-NIR imaging using TDI detectors and lightweighted optics in the 1-1.5m class (5 cm/pixel class)
K-Band Radar	Compact K-band imaging and sounding radars (nadir and sidelooking) for planetary sciences (small antennae, lower power)
IR Spectrometers	Advanced, multi-detector Fabry Perot IR spectrometers for trace-gas detection
Optical Communications	Mass efficient optical telecommunications systems capable of 100 Mbps to 1 Gbps from Mars or Venus orbit (to Earth) or up to 100 Mbps from Jupiter or Saturn would increase bandwidth by a factor of 10-100 and improve scientific ranging to spacecraft by a factor of 10-50 over RF methods.
Lidar Fiber Transmitters	Advanced fiber-based laser transmitters with 0.01 to 20 mJ pulse energy in the Green to NIR for lidars
3-D Imaging Flash Lidar	3-D Imaging Flash Lidar for Safe landing on planetary bodies by enabling Hazard Detection and Avoidance. 3-D Imaging Flash Lidar has also been identified as the primary sensor for Automatic Rendezvous and Docking.
Radar 3-D Imaging	Shallow, radar 3D imaging via a sounding-imaging-SAR would allow the lunar regolith to be mapped in 3D at spatial scales of 10-20m and vertically to 3-5m; the same could be done for Europa or NEO’s
Hyper-Resolution SAR	Hyper-resolution SAR enabled by wideband electronically steered array based technologies and advanced T/R switches and microwave power modules could enable sub-meter RADAR imaging of cloud-enshrouded planets such as Titan and Venus at scales of 50 cm to 1 m and have the equivalent impact as the optical high resolution imaging at Mars and the Moon (HiRISE and LROC)
Extended-Life IR Sensors	The first essential ingredient for success for a human mission to a NEO is to complete the NEO survey to identify the most interesting human-accessible targets. A space-based IR survey telescope in a heliocentric orbit ~0.65 to 0.72 Astronomical Units (AU) from the Sun will enable mapping of the remaining NEOs not visible from Earth-based observatories and identification of the orbital dynamic characteristics.
Soil Moisture using L-band GPS	Use the earth-surface "bounced" L-band GPS signal to measure changes in soil moisture with time to improve crop yields and climate models that utilize soil moisture.
Ocean wind speed measurement	Deploy small GPS bistatic receivers on commercial cargo aircraft to utilize ocean-reflected ("bounced") GPS signals for ocean wind speed measurement. Since GPS is available globally, high-resolution wind speed measurements can be taken over large portions of the ocean to study detailed weather patterns and storm development.

(MKIDs). Planetary and Earth Science missions require high-performance detectors from 0.2 to 20 µm. Sensitive IR detectors require cooling to reduce dark current noise and reach background-limited IR photo detection (BLIP), making them impractical for many planetary missions because of their volume, mass, and power consumption. However, the development of compact, efficient-low powers cryocoolers will enable the greater use of higher sensitivity detectors that are cooled for these missions. Solid-state γ-ray and neutron detectors with high-energy resolution and directionality are also needed for planetary Science instruments.

Electronic Technology: Electronics technologies were grouped in the following categories: radiation hardened, low noise, and high speed. Across all disciplines, reducing the volume, mass, and power requirements of instrument electronics are essential to maximizing the science return for future missions. Most instrument electronic systems use traditional printed wiring circuit boards that are populated with discrete components that number in the thousands, resulting in high mass and power consumption. In addition, the cost associated with the reliability and qualification of electronic systems with large component counts is high. One solution to this problem is the development of highly integrated electronics using advanced circuit design and a modern, high-density packaging technology for next-generation instrument systems.

Most future missions need significant technology advances in readout electronics for kilo-pixel or larger arrays. Spectrometers across a wide range of wavelengths, meanwhile, require fully digital back-ends for lower mass, higher speed, and reliability. Heliophysics missions need integrated electronics and sensor readouts that enable significant data compression. Future Earth science missions share a common need for low-noise, high-speed, and low- power readout integrated circuit (ROIC) electronics for large focal-plane instruments. Planetary instruments have special needs for high-performance and low-power electronics that can operate at extremely cold, or hot temperatures, and over wide temperature ranges. For missions to Mars, Titan, the Moon, comets and

Table 6. *Science Instruments Technology Challenges*

	Technology Metric	State of Art	Need	Start	TRL6	SMD Division
8.1.1 Detectors and Focal Planes	**8.1.1.1 Large Format Arrays**					
	NIR & TIR Detectors	Pixel array: 2k x 2k, Pixel size: 18 µm	4k x 4k 10 µm	2011	2014	Astro Earth
	TIR Spectrometer detectors (8ch, 3-12 µm)	Frame rate	256 Mpix/sec at 32 kHz	2012	2016	Earth
	UV & IR CCD arrays	Pixel array: 4k x 4k	10k x 10k	2011	2014	Earth Astro
	UV-VIS spectrometer, Hybrid arrays	Well Depth: Pixel array: 1k x 1k	1M electrons 4k x 4k	2010	2013	Earth Helio
	UV-VIS-NIR spectrom-eter ROIC	Pixel array: 256 x 256, Quantization level: 50% QE	1024 x 2048 > 90% VIS-NIR	2013	2019	Earth
	Backscatter lidar , CCD array	Quantum efficiency:	>70% at 355 nm; >90% at 532 nm	2012	2019	Earth
	8.1.1.2 Spectral Detectors					
	Spectrally tunable IR	Narrow-band/wide range 1 µm/ few µm	0.1 µm/few µm in 1-15 µm	2015	2018	Planet
	Spectrally tunable submm	Tunability @ x GHz 60 GHz @600 GHz	>100 GHz @600 >150 GHz@1200	2015	2018	Planet
	2D filter imager	80-120 nm, 30:1	80-120 nm, 3000:1	2012	2018	Helio
	8.1.1.3 Polarization Sensitive Detectors					
	Inflation Probe detector	Size, Pixel array, Temperature	100 x 100 mm 1k x 1k < 1K	2011	2020	Astro
	Polarization detectors for altimetery/dust	Switching speed, 50%, ~1 Hz	>90%, >50 Hz	2013	2018	Planet
	Dual-polarized multi-frequency feed array	Frequency bands, Polarization	9.6 to 17.2 GHz H/V all freq	2017	2022	Earth
	8.1.1.4 Photon-Counting Detectors					
	Detectors: visible photon-counting (CCD, APD or other)	Pixel array : 512 x 512, Quantum efficiency: 80%, 450-750 nm	1k x 1k > 80% 450-900 nm	2011	2020	Astro Planet
	NIR to UV photon detector (APD)	Pixel array, QE, (NEP)	256 x 256 >55% QE 10^{-14} W/Hz$^{1/2}$	2011	2015	Astro Earth
	Photon-counting detector	Wavelengths, QE	1064,532,355nm >80%; 80-200nm, >50%	2018	2024	Earth Helio
	8.1.1.5 Radiation-Hardened Detectors					
	Fast, low-noise, O/UV, IR detector	Pixel array 1K x 1K, Pixel rate 10 MHz, Read noise 100 e, Rad tolerance 50krad	4k x 4k, 60 MHz, 20 e- 3Mrad	2013	2016	Helio Astro, Planet
	8.1.1.6 Sub-Kelvin High-Sensitivity Detectors					
	X-ray detectors (micro-calorimeter)	Energy res.(6 keV) 4 eV, rate/pixel 300 c/s, Pixels: 36	2 eV 1,000 c/s 1600	2011	2015	Helio Astro
	FUV-EUV 2D detectors	80-200 nm, QE <20%	>50%	2011	2015	Helio
	Far-IR broadband, detector arrays	Sens. (NEP W/√Hz) 3e-19, Wavelength > 250µm, Pixels 256	3e-20 35-430µm pixels 4000	2011	2015	Astro, Earth, Planetary

	Technology Metric	State of Art	Need	Start	TRL6	Mission
8.1.2 Electronics	**8.1.2.1 Radiation Hardened**					
	Radiation-hardened electronics	TID tolerance, 0.1-1 Mrad	3 Mrad	2010	2020	Planet
	8.1.2.2 Low Noise					
	ROIC	Well: <100K e, Format: 4k x 4k, Speed: Low	>2 Me, 8k X 8k, >60 FPS	2013	2019	Earth Astro
	Low-noise electronics	Noise level: <1%, Temperature -55C to 125C	<0.01%, -180 C to125 C	2011	2020	Planet, Astro, Earth, Helio
	HV power supply	Voltage out, Eff= ~15%@20 kV, TID tolerance 0.1 Mrad	20 kV, >20%, 0.7 Mrad	2013	2019	Earth Helio
	8.1.2.3 High Speed					
	Fast electronics	Timing 10 ns, Dead T/event 300 ns	~3 ns, ~30 ns	2012	2014	Helio
	High-speed: altimetry	Freq: 200 Mz	2-8 GHz	2012	2020	Planet
8.1.3 Optical Components	**8.1.3.1 Starlight Suppression**					
	Coronagraph or occulter	Contrast Vis >1 x 10^{-9} Contrast mid-IR 1x10^{-5}	< 1 x 10^{-10} < 1 x 10^{-7} 1 x 10-11/image 20%, at V, I,	2011 2011	2016 2011	Astro
	Starlight suppression	Bandwidth: Passband: Partial	3 ksec, Broad	2011	2020	Astro
	8.1.3.2 Active Wavefront Control					
	Wavefront control	20nm	1-5 nm	2011	2020	Astro
	Wavefront sensing	10nm	1-5 nm	2011	2020	Astro
	Bandwidth	Varies	1 hz, 1-5 nm	2011	2020	Astro
	8.1.3.3 Optical Components					
	X-ray optics	1 as lens/15as mirror	.1/7 arcsec	2011	2014	Helio
	Instrument optics	Transmission: 90 % Uniformity: 80% Specific λ coating	T>97%, U>90%, λ 1-15 µm	2010	2020	Planet
	Filters/coatings	Temp range, bandpass Trans reflectivity	High res, cryo	2011	2020	Many
	Reflective filters	5 nm FWHM, 80% R	2 nm FWHM, > 90% R	2011	2014	Helio
	8.1.3.4 Advanced Spectrometers/Instruments					
	UV image slicer	5 slices, >300 nm wavelength range	20 slices 90 nm WR	2011	2014	Helio
	Advanced spectrometers	Miniaturization, 5-10 kg single func.	1-3 kg multi-function	2010	2020	Planet
	Spectroscopy components	Fabry Perot at 50K	50K IR 100K resn.	2011	2020	Many
	Wide FOV reflective imager	20 deg, 30 cm aperture	30 deg >60 cm	2011	2016	Helio

	Technology Metric	State of Art	Need	Start	TRL6	Mission
8.1.4 Microwave/Radio	**8.1.4.1 Integrated Radar T/R Modules**					
	Integrated radar T/R mods.	Power & Efficiency; 10-30W, 40%	10-30 W, 60%	2013	2020	Planet
	Ka-band power switch matrix	Power capacity	2.5kW pk, 110-165W av	2013	2015	Earth
	Dual-polarized multi-frequency microwave feed arrays (radar)	Frequency bands, Scanning range	9.6, 13.4, 17.2 GHz, >10-20 degrees	2017	2022	Earth
	Correlator	Power 224 μW @375 MHz	250 μW @ 1 GHz	2014	2020	Earth
	8.1.4.2 Integrated Radiometer Receivers					
	Integrated radiometer receivers	High freq.: THz; non-cryo, 100-ele array at 100 GHz	Quantum-limited noise at 30-110 GHz, cryogenic	2013	2020	Planet
	Low-noise cryogenic mm-wave amplifiers	Receiver noise temp @ 20K, 100K at 190 GHz	< 100 K at 180-270 GHz;	2015	2023	Earth
	Ka-band receiver	Phase stability, isolation, Bandwidth	~40 mdeg over 3 min., >80 dB, >200MHz	2013	2015	Earth
	Low-mass, low-noise broadband receiver	Noise level; Power; Mass	400K; < 50 mW; < 150 g	2014	2020	Earth
	G-band radiometer	Spatial resolution	Single feed 90-180 GHz	2011	2015	Earth
8.1.5 Lasers	**8.1.5.1 Pulsed Lasers**					
	Pulsed lasers for ranging altimeters, backscatter LIDAR	Profiling: Single, Lifetime: $6x10^8$, Sample rate: 1-40 Hz	Multi-beams, >109 shots, 40 Hz-100 kHz,	2013	2020	Planet
	Laser altimeter (1μm)	Wallplug eff: 10%, Multi-beam array: 9 beams @ 222 μJ/beam	20%, 1000 beams @ 100μJ/beam	2012	2018	Earth
	Tunable NIR/IR laser (gas detection)	Wall plug: 2%, Single frequency: 40 μJ	>10%, 100 μJ	2012	2018	Planet
	0.765/1.572/2.05 μm pulsed	Output energy; Rep rate; Efficiency	>3/3/65 mJ; 10 kHz / 10kHz / 50 Hz; 3.5/7/5%	2012	2014	Earth
	Multi-freq lasers - 2 μm pulsed	Output energy; Rep rate; WPE; Laser lifetime	250 mJ; 5Hz; 5%; 500 M-shots	2014	2024	Earth
	355 nm, single-frequency pulsed laser	Output energy; Pulse rep Rate; Laser lifetime	32 to 320 mJ/Pulse; 120 to 1500 Hz; >3 yrs	2014	2024	Earth
	Damage-resistant UV laser at 355 nm	Energy; Repetition rate; Efficiency; Lifetime	300 mJ; 100Hz, 10%; 3-5 Years	2012	2019	Earth
	8.1.5.2 CW Lasers					
	CW lasers for fluorescence	Peak power at, <250 nm: 10 mW	>100 mW	2013	2020	Planet
	CW tunable NIR/IR for gas	Some λ regions	1-15 μm	2013	2020	Planet
	1.6 μm CW laser	Power; Module; Efficiency	35W; 1; 10%	2012	2014	Earth
	1.26 μm CW laser	Power; Module; Efficiency	20W; 1; 8%	2012	2014	Earth
	- 2 μm CW seed laser	Power: 60 mW	100 mW	2014	2024	Earth
	LISA laser	Single frequency Stable noise	Freq. Comb Ultra Low Noise	2015	2020	Astro
	CW laser	Power: 10 mW	>50 mW	2015	2021	Earth
	Diode lasers (magnetometers)	Power at 1.083 μm 1 mW	>10 mW	2013	2020	Planet
8.1.6 Thermal Cryogenic/	**8.1.6.1 4-20 K Cryo-Coolers for Space**					
	Efficient flight 4 K cryocooler	Heat lift: 20 mW @ 6K, Efficiency: 10Kw/mW	>20 mW @ 4 K <10 W/mw at 4 K	2015	2023	Earth
	8.1.6.2 Sub-Kelvin Coolers					
	Continuous sub-K refrigerator	Heat lift <1 μW Duty cycle 90 %	> 10 uW 100 %	2011	2015	Astro

asteroids, electronics are required to operate over a low/wide temperature (-230 ℃ to +125 ℃) range.

Optical Component Technology: Optical component technologies were grouped in the following categories: starlight suppression; active wavefront control; and advanced spectrometers/instruments. Improvements in optical components complement improvements in detectors. Performance requirements include high throughput, large FOV, high stability, high-spectral resolution, and high contrast and uniformity at many different temperatures and within a variety of packages.

Optical technology development includes both incremental improvements that further push the state of the art and breakthrough technologies that can enable entirely new instrument or even observatory architectures. There are a wide variety of instrument types optimized for each science need and only some of the most critical technologies are described here. Competitive technology opportunities best identify new ideas that are often based on improving optical space via the parameters listed above. The technology developments then lead to instrument incubator and testbed activities to support small, medium, and large missions. In general, starlight-suppression and wavefront sensing and control technologies work with observatory developments to enable large missions. Advanced spectrometer/instrument subsystems enable and can be used in smaller, midsized, or larger instruments.

Microwave/Radio Transmitter and Receiver Technology: Microwave/radio transmitter and receiver component technologies were grouped in the following categories: integrated radar T/R modules and integrated radiometer receivers. It includes active microwave instruments (radar), passive radiometers, navigation sensors (GPS), and crosscutting technologies, such as cryogenic coolers, and radiation-hardened electronics. The frequency range runs from 30 kHz to 3 THz. Investments include low-noise receivers, array-system and cryogenic receiver demonstrations, prototype ASIC correlators, and field demonstrations.

Challenges include extending low-noise amplifier technologies to >600 GHz, reliable low-power high- speed digital and mixed-signal processing electronics and algorithms; demonstration of RFI mitigation approaches, and algorithms for future RFI environments to 40 GHz and beyond; large-array receiver demonstrations; low-cost scalable radiometer integration technologies; large (D/lambda>8000) deployable antennas. Technology development is needed for lower-mass receiver front ends, intermediate frequency signal processors, and microwave spectrometers that analyze the down-converted signal with high-spectral resolution.

Laser Technology: Lasers/lidar component technologies were grouped in the following categories for this roadmapping activity: pulsed lasers and CW lasers. Laser/lidar remote sensing encompasses subsystems and components for surface elevation and atmospheric-layer height measurements; transponder and interferometer operation for precise distance measurements; scattering for aerosol and cloud properties and composition; carbon-dioxide measurement; and Doppler velocity determination for wind measurements. Wavelengths range from 0.3 to 2 μm. The key technologies include lasers (high power, multibeam and multiwavelength, pulsed, and continuous wave), detectors, receivers, and scanning mechanisms. For laser-ranging systems, the primary need is a continuous-wave laser with suitable power (>50 mW), narrow linewidth (<2 MHz), and long lifetime (>5 years). The main technology challenge is the lack of manufacturers who can provide space-qualified laser pump diodes. Laser technology is advancing at a very rapid rate with order-of-magnitude increases in key parameters (e.g., 30% wall-plug efficiency). Similar advances are occurring in detector technology.

Cryogenic & Thermal Systems Technology: Cryogenic/thermal-system component technologies were grouped in the following categories for this roadmapping activity: 4-20 K and sub-Kelvin cryo-coolers. Cryogenic and thermal systems include both passive and active technologies used to cool instruments & focal planes, sensors, and large optical systems. Active cooling is required to push the instruments, sensors, large optics and structures below the temperature limits of radiators and passive methods. At present, multiple technologies are being investigated and developed to cool to the 50–80 K range. However, a significant technology gap exists between recent progress and what is required to produce reliable, long-life, efficient thermal systems that can cool instruments, telescopes, and their associated optics to <20 K. Technology investments are needed to raise the 4 K cryo-cooler to TRL5/6, develop a low-power, low-compressor temperature cryo-cooler operating at 30-35 K for planetary missions, and develop compact, efficient drive electronics scalable to powers ranging from 60-600 W.

Remote-Sensing Instruments/Sensors Push Technologies: The table below captures the high priority push technologies received from the NASA centers. These push technologies will provide a quantum leap in measurement capabilities for both science and human exploration.

2.2.2.2. Observatory Technology Challenges

Observatory technologies are necessary to design, manufacture, test, and operate space telescopes and antenna, which collect, concentrate and/or transmit photons. Observatory technologies enable or enhance large-aperture monolithic and/or segmented single apertures as well as structurally connected and/or free-flying sparse and interferometric apertures. Applications span the electromagnetic spectrum, from X-rays to radiowaves. Based on the needs of planned and potential future NASA missions summarized in Table 7, it is possible to define six specific enabling observatory technologies:

- Large-Mirror Systems: Grazing incidence
- Large-Mirror Systems: Normal incidence
- Large Structures and Antenna: Ultra-stable structures
- Large Structures and Antenna: Large-deployable/assembled structures
- Large Structures and Antenna: Control of large structures
- Distributed Aperture: Formation flying

These technologies support three primary applications: X-ray astronomy, UVOIR astronomy, and microwave/radiowave antenna. Figure 4 illustrates the technology-development roadmap for observatory technologies.

For all applications, regardless of whether the incumbent system is 0.5 m or 5 m, the fundamental driving need is larger-collecting aperture with better performance. The technologies for achieving performance are the ability to manufacture and test large-mirror systems; the structure's ability to hold the mirror in a stable, strain-free state under the influence of anticipated dynamic and thermal stimuli; and, for extra-large apertures, a method to create the aperture via deployment, assembly, or formation flying — where formation-flying technology is an actively controlled virtual structure. One non-telescope application is the manufacture, deployment, in-plane and formation-flying control of an external-occulting starshade to block starlight for exo-planet observation.

Similar optical technologies are needed to design, manufacture and test science instruments and telescopes. A good example is with WFSC. In

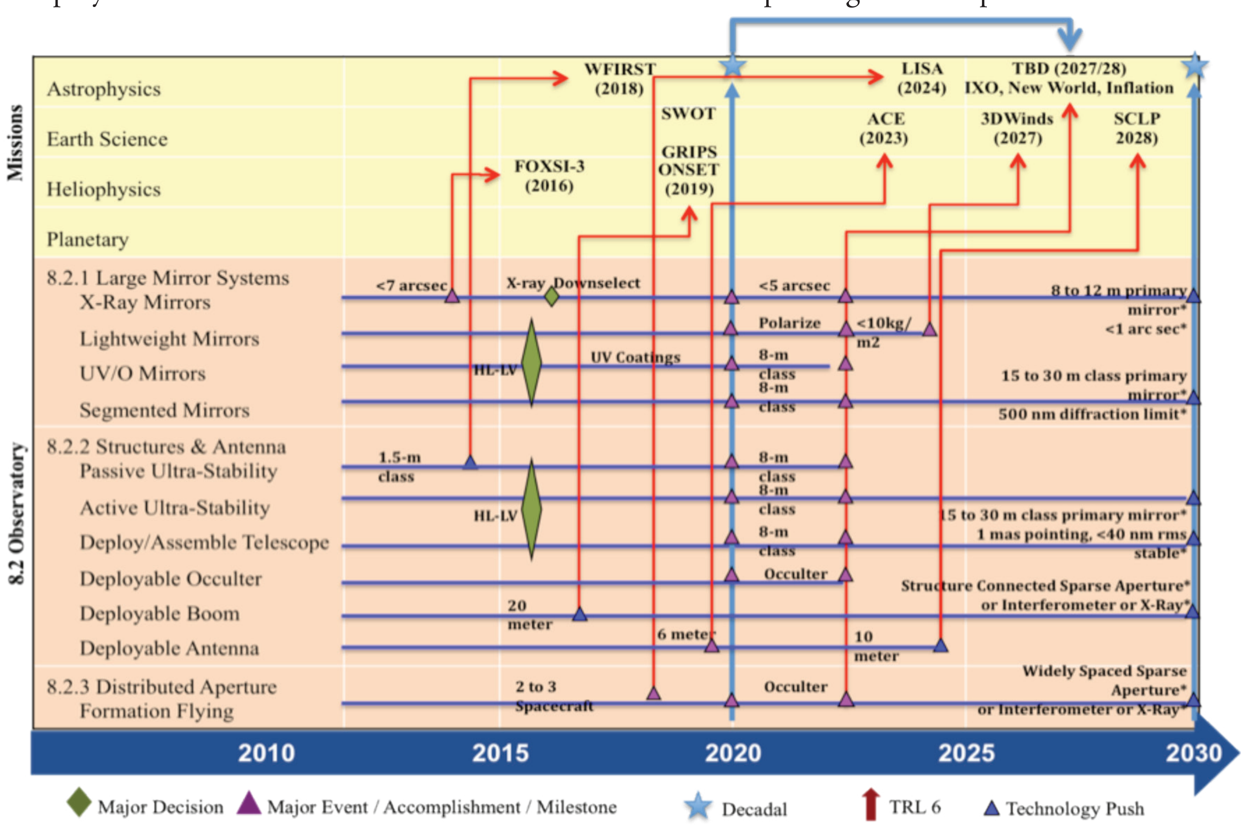

Figure 4. *SIOS Observatory Technologies Roadmap*

DRAFT

Technology	Description
8.2 Observatories	
Synthetic Aperture Imaging Lidar (SAIL)	Synthetic Aperture Imaging Lidar (SAIL) for hyper-resolution imaging and 3D ranging (range imaging). SAIL methods could map dynamics of planetary surfaces on Mars (polar caps), Titan (moving landscapes), and even on Europa much more efficiently than current single beam or multi-beam approaches. SAIL may be a method worth pursuing for ICESat-3 in the 2020's to rapidly build up 3D geodetic maps of the ice covered surfaces of Earth
Super High-Resolution Imaging of High-Energy Photons	The technology need is to build a large area (much larger than current optics) high energy optic and then have it fly it formation with the imaging spacecraft
Radar Arrays	Wideband active electronically steered array radar with lightweighted antennae
Precision Interferometry	Requires CW single-frequency and frequency-stabilized lasers for space (GSFC applications so far are pulsed). Digital techniques including coded modulation for time-of-flight resolvable interference, and flexible in-flight changes. Time-Domain Interferometry (LISA's equal-path-length synthesis techniques).
Hyper-Resolution Visible-NIR	Hyper-resolution Visible-NIR imaging using lightweighted optics in the 1-1.5m class (5 cm/pixel class)
K-Band Radar	Compact K-band imaging and sounding radars (nadir and sidelooking) for planetary sciences (small antennae)
Conductive Carbon Nanotubes	Spectacular new material for the fabrication of lightweight antennas could be enabled by the unbelievable conductivity of individual carbon nanotubes.
Deployable Large Aperture Telescopes	Ultra low mass/volume large deployable large aperture telescopes (>2 meter) for direct detection LIDAR. Concepts include inflatable fresnel, deployable reflector and petal-based techniques.
High stability optical platforms	Includes optical benches, telescopes, etc, requiring passive thermal isolation for temperature stability. Hydroxide or silicate bonding for precision alignment capability and dimensional stability. Precision materials such as Silicon Carbide and single crystal silicon, Zerodur

addition to being implemented inside the science instruments, optical-component technologies provide feedback to operate the space telescope. Other important technologies include validated performance models that integrate optical, mechanical, dynamic, and thermal models for telescopes, structures, instruments, and spacecraft. These technologies enable the design and manufacture of observatories whose performance requirements cannot be tested on the ground. Another Push technology includes new materials to enable ultra-stable large space structures; terabit communication; and autonomous rendezvous and docking for on-orbit assembly of very large structures.

Chandra, HERO, FOXSI, XMM, and the soon-to-be launched NuSTAR currently define the state of the art in X-ray astronomy. Pull requirements for X-ray astronomy are defined by IXO and FOXSI-3. Missions like Gen-X define X-ray 'push' requirements. Hubble, JWST, and commercial imaging systems, such as QuckBird, represent the state of the art in UVOIR. Pull requirements for UVOIR are defined by WFIRST, TPF-C, and ATLAST-8 or ATLAST-9. Missions like ATLAST-16 define push requirements for extremely large space telescopes (ELST) in the 15- to 30-m class range. GRIPS, ONEP, SWOT, ACE, and SCLP represent future pull requirements for antenna and booms.

Finally, the most important metric for all future large telescopes must be cost per square meter of the collecting aperture. Assuming that total mission budgets always will be limited to a few billion dollars, the only way to afford a larger telescope is to reduce areal cost. Historically, a space telescope's inflation- adjusted cost has decreased by 50% every 17 years. Investment is required to accelerate this trend.

Observatories Push Technologies: The table below captures the high priority push technologies received from the NASA centers that focused mostly on large-area structures, telescopes, and antennas. Additionally, synthetic aperture development will be pushed to new levels as technology transitions to 3D range imaging. Observatory push technologies apply to Earth missions (LIST and beyond), and to NEOs. These push technologies will provide a quantum leap in measurement capabilities for both science and human exploration.

2.2.2.3. In-Situ Instruments/Sensors Technology Challenges

In-Situ Instruments/Sensors technologies enable or enhance a broad range of planned and potential missions in the next two decades. These technologies can be grouped into three general categories that collect and/or sense: (1) charged and neutral particles; (2) magnetic and electric fields and waves (e.g., gravity); and (3) chemical, mineralogical, organic, and in-situ biological samples. Technologies related to the first two categories are required for Astrophysics, Heliophysics, and Planetary missions, while in-situ sampling technologies are required only in support of planetary missions (none identified for Earth). Table 8 summarizes the required sensor technologies for each category, their current state of art, the needed performance, and the type of missions that they will

Table 7. *Observatory Technology Challenges*

	Technology Metric	State of Art	Need	Start	TRL6	Mission
8.2.1 Large Mirror Systems	**8.2.1.1 Grazing Incidence**					
	1 to 100 keV FWHM resolution	10 arcsec	<5 arcsec	2011	2014	FOXSI-3
	Aperture diameter FWHM resolution Areal density; Areal cost	0.3 m^2 15 arcsec 10 kg/m^2	>3 m^2 <5 arcsec	2011	2020	IXO
	Aperture diameter FWHM angular resolution Areal density (depends on LV) Active Control	0.3 m^2 15 arcsec 10 kg/m^2 No	>50 m^2 <1 arcsec 1 kg/m^2 (depend LV) Yes	2011	2030	Push, GenX
	8.2.1.2 Normal Incidence					
	Size & polarization Areal density	Planck, ~20 kg/m^2	1.6 m, <6 kg/m^2	2011 2018	2020 2024	ITP, 3DWinds
	Aperture diameter Figure Stability (dynamic & thermal) Reflectivity Areal density (depends on LV) Areal cost	2.4 m < 10 nm rms --- >60%, 120-900nm 240 kg/m^2 $12M/$m^2$	3 to 8 m <10 nm rms >9,000 min >60%, 90-900 nm 20 (or 400) kg/m^2 <$2M/$m^2$	2011	2020	NWTP, UVOTP
	Aperture diameter Areal density (depends on LV) Areal cost	6.5 m 50 kg/m^2 $6M/$m^2$	15 to 30 m, 5 (or 100) kg/m^2, <$0.5M/$m^2$		2030	Push, EL-ST
8.2.2 Large Structures & Antenna	**8.2.2.1 Passive Ultra-Stable Structures**					
	Thermal stability	Chandra	WFOV PSF Stability	2011	2014	WFIRST
	Aperture diameter Thermal/dynamic stability Line-of-sight jitter WFE Areal density (depends on LV) Areal cost	6.5 m 60 nm rms 1.6 mas 40 kg/m^2 $4 M/$m^2$	8 m 15 nm rms 1 mas <20 (or 400) kg/m^2 <$2 M/$m^2$	2011	2020	NW/UVO
	8.2.2.2 Deployable/Assembled Telescope Support Structure and Antenna					
	Antenna aperture Antenna aperture Surface figure	5 m 1.5 mm rms	6 m > 10 m <0.1 mm rms	2013 2016	2019 2023	ACE, SCLP
	Boom length Stiffness Pointing stability		≥ 20 m 10^7 N m^2 0.005 arcsec roll/3 min	2011	2014	GRIPS, ONEP, SWOT
	Occulter diameter	Few cm	30 to 100 m	2011	2020	NWTP
	Aperture diameter	6.5 m	8 m	2011	2020	NW/UVO
	Aperture diameter	6.5 m	15 to 30 m		2030	EL-ST
	8.2.2.3 Active Control					
	Occulter pedal control Occulter modal control Boom tip control		< 0.5 deg < 0.1 mm rms ~0.5 deg	2011 2012	2020 2014	NWTP, GRIPS
	Aperture diameter Aperture diameter Thermal/dynamic stability Line-of-Sight jitter WFE Areal density (depends on LV) Areal cost	6.5 m 6.5 m 60 nm rms 1.6 mas 40 kg/m^2 $4 M/$m^2$	8 m 15 to 30 m 15 nm rms 1 mas <20 (or 400) kg/m^2 <$2 M/$m^2$	2011	2020 2030	NW/UVO, Push, EL-ST
8.2.3 Distributed	**8.2.3.1 Formation Flying**					
	Range		10,000 to 80,000 km	2013	2016	LISA
	Separation control Lateral alignment Relative position Relative pointing	2 m 5 cm rms 6.7 arcmin rms	100 to 400 ±0.1 m ±0.7 m wrt LOS < 1 cm rms < 1 ±0.1 arcsec	2011	2015 2024 2030	ONEP, Occulter, NWTP, Push

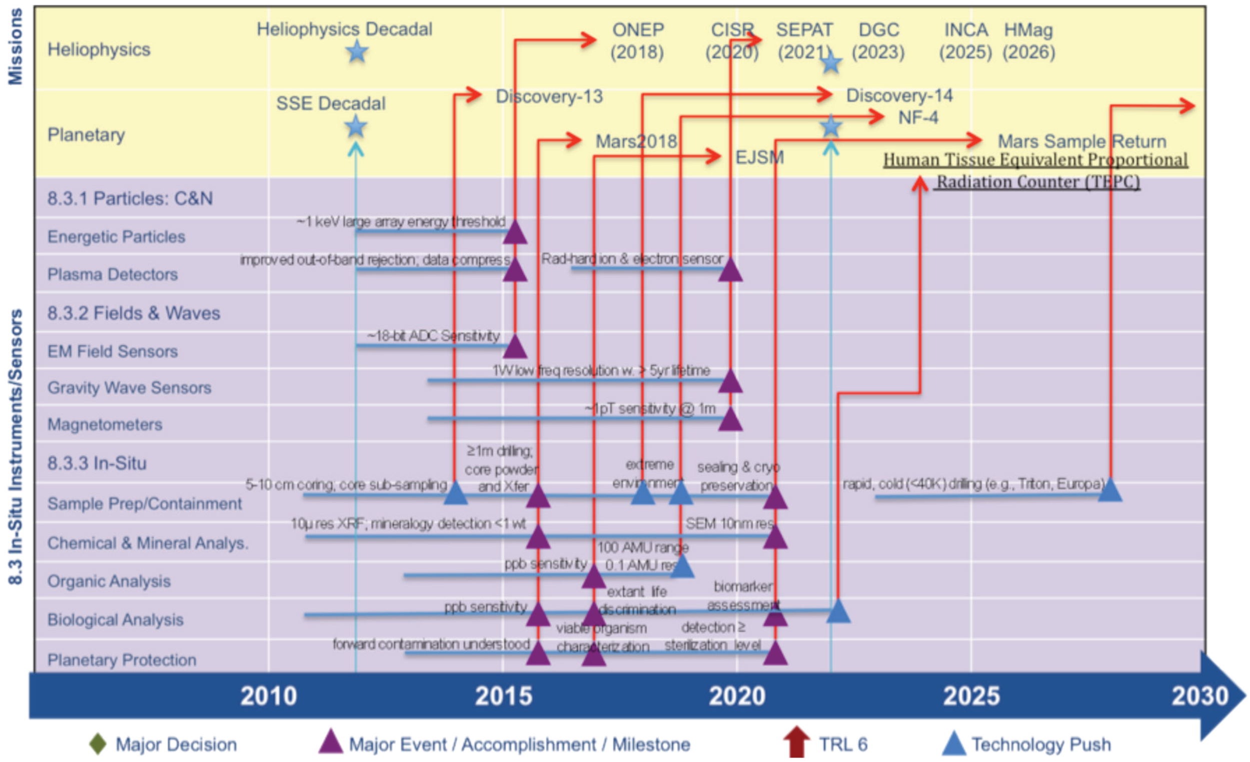

Figure 5. *SIOS In-Situ Instruments/Sensors Technologies Roadmap*

Technology	Description
8.3 In-Situ Instruments/Sensors	
Atomic Magnetometers	This technology has the potential to greatly reduce the resources required to execute vector magnetic field measurements.
Neutron Spectroscopy	In situ dynamic neutron spectroscopy with active sources and collimated detectors (beyond MSL's DAN)
Scanning Electron Microscope	In-situ scanning electron microscope imaging at 1 um and smaller for planetary surfaces
X-Ray Imaging	In-situ X-ray imaging for definitive mineralogy without sample preparation
Human Tissue Equivalent Proportional Radiation Counter (TEPC)	Current SOA is a space station devices operating in near-atmospheric condition that measure dosages on crew. Robust sensors capable of operating for long periods in environment of space are needed to measure the radiation at the destination as well as during the journey. Previous TEPCs on Mars missions have mostly failed en-route. Until we get better data on interplanetary environment, the JSC human health group wants to limit human trips to 150 days or less.
Tricorder Health Monitoring System	As a related topic to humans in space, a monitoring system that will provide a reading of astronauts' health.

enable or enhance. Figure 5 illustrates the technology-development roadmap for sensor-systems technology. Major near-, mid- and far-term sensor-system technology-development challenges in each of these three areas include (but are not limited to):

Particle & Plasma Sensors: Particle-sensor technologies were grouped in the following categories for this roadmapping activity: energetic particles and plasma detectors. Technology requirements for particle and plasma detectors addressing Heliophysics needs are varied and depend on the space environment being measured. For solar wind observations and energetic particles in planetary and near-Earth space environments, the state of art is a complement of an energy-scanning electrostatic analyzer with a micro-channel plate (MCP) detector. Another technology is a solid-state detector to cover the entire energy spectrum. Volume, mass, and power savings could be realized by integrating two instruments into one to enable future heliophysics and planetary missions. For plasma sensors, we need to explore techniques to remove out-of-band energies and composition and minimize mass and power resources. For these sensors, radiation-hardened and miniaturized high-voltage power supplies are required.

Fields and Waves Sensors: Fields and wave-sensor technologies were grouped in the following categories for this roadmapping activity: EM field sensor and gravity wave sensors; magnetometers. Improved knowledge of interplanetary space and its coupling to planetary-body magnetospheres and ionospheres, including the Earth, rely on understanding the flow of mass and energy. Observing the dynamic nature of electric and magnetic fields in these regions is key to achieving this understanding. The technology development for AC and DC magnetic and electric field sensors is primarily focused on increasing sensor sensitivity and developing robust and efficient deployment mechanisms and platforms. The magnetic and electric isolation required for the sensors and spatial locations is critical.

In-Situ Sensors: In-situ sensor technologies were grouped in the following categories for this roadmapping activity: sample handling, preparation and containment; chemical and mineral analysis; organic analysis; biological detection and characterization; and planetary protection. Advances in in-situ sensor technologies will enable and enhance the science return from planetary missions planned over the next 20 years, including surface exploration, subsurface access, sample return, and scout missions prospecting for in-situ resources. Many of these missions are not possible without adequate in-situ sensor technology investment starting as early as 2011. The criticality of in-situ sensor technologies is determined by the normal evolution of planetary exploration. That is, solid-body research typically involves a series of missions to a given target following this chronological order: flyby, orbiter, surface lander, rover, subsurface exploration, and sample return. The first four mission architectures already have been achieved on Mars (and to some extent, other planetary targets). Future sensor technologies, therefore, need a strong focus on enabling the next logical step — subsurface-access missions. Such technology is valuable for airless bodies where geology is the prime interest, but it is essential for exploring atmospheric bodies where microbial life could exist below the surface (Mars, Titan).

Techniques for acquiring, processing, transferring, delivering, and storing subsurface samples are the most critical and currently represent a huge gap between needed and available in-situ sensor technologies. The Mars Sample Laboratory (MSL) Sample Acquisition, Sample Processing and Handling (SA/SPaH) system is the state of art for sample acquisition. For the Mars 2018 mission and beyond, however, technologies will be needed to drill for subsurface samples to 1 m or more and to collect intact cores to 5-10 cm with selective sub-sampling. Post-acquisition processing represents another technology gap for which neither the MSL SA/SPaH scoop and power system nor the MER Rock Abrasion Tool (RAT) system will adequately address future challenges. These systems only allow analysis of materials that are either sieved from the soil at < 150 μm or drilled from outcrops of rocks that are larger than 21 cm in diameter, leaving a good part of the Mars surface unsampled. The problem is worsened under microgravity and vacuum conditions, or with samples that are not dry powders. For example, current technologies are not capable of handling unconsolidated materials in microgravity, as would be required in a NEO mission. The challenges facing sample-preparation and delivery systems (including drilling, crushing, sieving, proportioning, sample movement, sample in-

Table 8. *Sensor-Technology Challenges*

	Metric	State of Art	Need	Start	TRL6	Mission
8.3.1 Particles	**8.3.1.1 Energetic Particle Detectors (>30 keV – N MeV)**					
	Energy threshold	~10 keV w. limited array	~1 keV in large arrays	2013	2016	Helio, Planet
	8.3.1.2 Plasma Detectors (<1 eV – 30 keV)					
	Environment tolerance; data handling	Polar	Rad-hard ion & electron sensors, improve out-of-band rejection, data compression	2013	2016	Helio, Planet
	8.3.1.3 Magnetometers (DC & AC)					
	Sensitivity	~10 pT @ 3-10 m	~1 pT @ <1m	2013	2020	H, P
8.3.2 Fields & Waves	**8.3.2.1 EM Field Sensors (DC & AC)**					
	Sensitivity; Operations	8-bit ADC; operations on Polar, FAST, THEMIS	18-bit ADC; robust deployment, fast observations	2013	2016	Helio, Planet
	8.3.2.2 Gravity-Wave Sensors					
	Low-Freq Sensitivity	30 mW w. <1 yr lifetime	~1 W w. >5 yr lifetime	2013	2020	A; H; P

	Metric	State of Art	Need	Start	TRL6	Mission
8.3.3 In-Situ	**8.3.4.1 Sample Handling, Preparation, and Containment**					
	Sample acquisition	MSL: SA/SPaH ExoMar: drill	Subsurface drilling ≥ 1 m; intact cores 5-10 cm length	2011	2014-2016	Planet
	Sample preparation	MSL: SA/SPaH; MER: RAT; ExoMars: jaw crusher	Core sub-sampling; powdering for XRD, GC-MS	2011	2016	Planet
	Sample transfer and delivery	MSL: Dry powder aliquot transfer w. < 5% contamination in gravity atm.	Transfer of various sample types (powder, ice) under many conditions (μG, vac.)	2011	2016	Planet
	Sample temperature control	Limited temperature control	Cryogenic & sealing, preserve volatile components	2011	2018	Planet
	Contamination & sample integrity	Phoenix: pre-launch steril. & cruise biobarrier; MSL: sample chamber clean.	Sample control & monitor for <0.1% cross-contamination	2011	2018	Planet
	8.3.4.2 Chemical and Mineral Assessment (Beyond APXS)					
	Wet chem. (pH, eH) & dissolved solids	Phoenix WCL	Measure sample dry wt., dissolved ions to 1 ppm	2011	2016	Planet
	Elemental composition (LIBS, XRF)	MSL XRD/XRF: whole sample analysis; component- limited performance, 0.5 wt% elemental separation	Spatial resolved XRF w. lat res ~10 μm; High eff. XR tubes; time-gated detect; 0.1 wt%, low atomic # (<18) capability	2011	2016	Planet
	Mineralogy (Raman, XRD, IR and UV spectrometers)	MSL CheMin: detect limit few wt%; ExoMars Raman w. 10s μm imagery/analysis	Detect limit <1 wt%; reflection mode XRD wo/ sample prep; spatially resol. Raman	2011	2016	Planet
	Microscopy	MSL MAHLI: 15μm res; Phoenix MECA: 4μm/pix clr	SEM imaging w. 10 nm res; Hyperspectral micro imaging	2011	2020	Planet
	8.3.4.3 Organic Assessment (Beyond INMS)					
	Detection sensitivity & contamination	Phoenix: ppb sensitivity with ppm contamination	ppb sensitivity; non-thermal methods, contamin. prevention	2011	2017	Planet
	Mass range & resolution	Cassini INMS: Range: 100 AMU; Res: 0.1 AMU	Range: >100 AMU; Resolution: <0.1 AMU	2011	2019	Planet
	8.3.4.4 Biological Detection & Characterization					
	Biomarker detection & characterization	Characterize viable organisms that are culturable; terrestrial contamin > detection limits	Biomarkers quantitative assessment w. ppb sensitivity; terrestrial contam prevention	2011	2016	Planet
	Complex Organic Polymer	ExoMars	ppb sensitivity	2011	2016	Planet
	8.3.4.5 Planetary Protection (PP)					
	Organism detection (sensitivity/breadth)	Characterization of viable organisms that are culturable	Characterization of any viable organism	2013	2016	Planet
	System & component sterilization	DHMR sterile w. detect < sterile; ppb organic contamin	DHMR & e-beam irrad w. detection ≥ sterilization level	2013	2016	Planet

sertion, etc.) create a need for sensors (like XRD/XRF) that can analyze samples without post-acquisition preparation and delivery. These likely would be arm-based in-situ sensors that would not require sample insertion, reducing the need for complicated acquisition and handling systems. Such sensor development represents a technology push that would broaden the range of feasible subsurface access missions. Technology gaps also exist for sample post-delivery, including those that enable temperature control during containment and storage. The technology is required to preserve icy or volatile components and enable control and monitoring of contained samples to limit cross-contamination to less than 0.1%.

Other in-situ sensor-technology challenges for future missions include techniques in chemical and mineral assessment, organic analysis, biological detection and characterization, and planetary protection. The state of art for each and needed technology advances are summarized in Table 8.

In-Situ Instruments/ Sensors Push Technologies: Push technology inputs provided by NASA's centers focused mostly on adapting geophysical analytical techniques for use on NEOs, planets, and other planetary targets of opportunity.

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

SIOSS technologies have direct, indirect, and game changing interdependencies with all the other technology areas (Table 9). These interdependencies flow both ways. A direct interdependency is one where a technology development in one area enables or enhances another area to achieve its performance metrics. An indirect interdependency is one where a development in another area changes the need for or the metric requirement for technology. A game changing interdependency is one where a breakthrough in another area enables a desired but previously inconceivable mission.

Examples of direct interdependencies of SIOSS technology impacting other technology areas (TA) include long-lived high-power lasers and single photon detectors for optical communication; large aperture deployable solar concentrators for space power and solar thermal propulsions; machine vision systems to aid human and autonomous operations ranging from the assembly of flight hardware to AR&D to 3D terrain descent imaging. A common theme for many TA areas was advanced integrated health monitoring sensors for applications ranging from jet engines, to launch vehicles to human health systems and non-destructive evaluation instruments. Sensor systems are critical to many navigation needs, including formation flying — both in space and commercially. Examples of indirect interdependencies include: how feedback from planetary science missions might modify requirements of human-rated planetary mission vehicles and systems; how Earth science data might modify requirements for commercial aviation systems or terrestrial launch operations. A potential game changing SIOSS technology is a quantum-entangled optical comb clock to enable a deep space positioning system.

Examples of direct interdependencies of how other technology impacts SIOSS includes milli-Newton and micro-Newton thrusters, drag-free propulsion control, and accelerometers that enable advanced gravitation sensors; robotic systems that enable various planetary in-situ sensing; new materials for extreme environments such as Venus or Titan, nano-technology for new miniaturized biological or chemical sensors; or sub-20K cryocoolers for infrared to far-infrared optical systems and detectors. Examples of other TA technologies required to enable SIOSS technology missions include downlink communication of terabits of data; solar sails to reach and maintain orbits; descent systems, and aero-capture systems. Potential game changing technologies include a shared power and communication infrastructure at Sun-Earth L2; in-space robotic servicing; or human assisted in-space assembly.

Of particular interest was the interaction between the SIOSS team and the Human Exploration Destination Systems (HEDS) Team. HEDS technology requirements include improved sensors and instrumentation for characterizing destination sites. Included in this assessment are those technologies needed for macro characterization of the destination target, including sensors incorporated onto a space-based observatory and those needed for in-situ characterization, including sensors on a robotic precursor or early crewed mission.

While SIOSS concentrated primarily on SMD applications (astrophysics, Earth, heliophysics and planetary science), the technology is applicable to the entirety of NASA missions. Table 9 details how SIOSS technology can enable applications related to other NASA mission directorates.

Table 9. *Interdependencies between SIOSS Technology and other Technology Areas*

Technology Area	Other TA Technology required by SIOSS	SIOSS Technology required by Other TA
TA1: Launch Propulsion	All: Affordable access to space Multiple: Medium lift vehicle MSR: Mars ascent vehicle PUSH: Heavy lift vehicle	IHM: Sensors for cryo and high-temperature applications; functional status, flows, motions; fault and anomaly detection; strain, temperature, vibration, acoustic; & power, COM: Wireless communication source/receive
TA2: In-Space Propulsion	Multiple: Electric/ion propulsion LISA, GRACE-II: Micro-Newton to milli-Newton thrusters Heliophysics: Solar sails, solar electric	IHM: Sensors for cryo and high-temperature applications; functional status, flows, motions; fault and anomaly detection; strain, temperature, vibration, acoustic; & power STP: Optical concentrator accuracy and performance (from 50-60% to 85-90%). BEP: High-power lasers, tracking & pointing
TA3: Space Power & Storage	Heliophysics & Planetary: Radioisotopes PUSH: Power 'grid' at L2	PVP: Photovoltaic sensors with large area, quantum efficiency (> 50%), single photon conversion, cryogenic & high-temperature operation, radiation hardened WPT: Laser, radio & microwave transmitters and receivers for power beaming, transmit power and throw distance; BEP; Charge/Power UAVs, GEO satellites, or deep space missions
TA4: Robotics	Mars 2018, NF 4, MSR: Rovers NF 4: Low-g mobility, sample acquisition & containment NF 4: Aerobots in extreme environments (Venus, Titan) MSR: Automatic rendezvous and docking PUSH: Robotic servicing PUSH: Robotic assembly	OR&PE: Requires fusing multiple-sensing modalities and perception functions, including machine vision, stereo vision, structured light, lidar and radar; lighting Feedback: Sensors for state, motion control; proximity, tactile, contact and force sensing to reach, grasp and use objects; avoiding hazards; telepresence for humans AO: Sensors for proximity, orientation, acceleration, velocity, docking status; terrain characterization; navigation 3D perception, active optical ranging
TA5: Com & Nav	General: Terabit communication General: GPS receivers for all LEO science missions LISA, GRACE-II: Gravitational reference system, accelerometers & drag-free control Planetary: Space position system PUSH: Precision formation flying	COM: RF and optical technology to transmit/receive >500 Mbps from Mars; low-noise single photon detectors; acquisition, tracking and pointing control; laser power and lifetime; send/receive telescope/antenna size; optical com for telemetry downlink of IHM data during launch; PNT: RF and optical technology for precision positioning and ranging; autonomous rendezvous, proximity operations and docking; star trackers, target imaging; formation flying requires relative motion and proximity sensors; flash lidar sensors, visible and infrared cameras, radar, radiometrics, rangefinders; space position networks; optical combs for system-wide clock synchronization PUSH: X-ray detectors and source for X-Ray Com and Nav; neutrino detectors and sources for neutrino com and nav; quantum-entangled photon communication
TA6: Human HAB	PUSH: Human in-space assembly and servicing PUSH: Human surface science	EMS: Sensors to detect crew-protection emergency conditions: fire, radiation, chemical, and biological hazards Health: Sensors to detect, predict, and treat crew health Weather: Sensors to monitor and forecast space weather
TA7: Human Exploration	PUSH: Heavy lift vehicle PUSH: Human in-space assembly and servicing PUSH: Human surface science	Destination Characterization: Ground & space telescopes to survey NEO population; missions to NEOs & other destinations (Moon, Mars, etc.); science instruments and sensor systems (imaging, spectroscopy, topographical, radiation, etc.) IHM: IHM sensors for spacesuits, hab system, transportation systems; non-destructive evaluation Optical Material: High-strength lightweight windows; deployable, shape-changing solar concentrators for power and thermal energy
TA9: Entry, Descent & Landing	MSR: Descent Systems NF 4: Extreme environment EDL (Venus, Titan) Planetary: Landed payload mass for sample- return missions; long-lived surface landers; robotic airships & airplanes; thermal protection materials	EDL: Advanced sensing (passive & active optical, IR & radar imaging & 3D profiling) for terrain tracking, hazard detection and event triggers, and guidance for terminal descent IHM: High-temperature systems capable of direct heat flux measurements, in-situ measurements in flexible TPS, and shock layer radiation measurements in ablative TPS Planetary: SIOSS technology to characterize planetary atmospheres, environments and weather (including wind & dust) to develop and validate models critical for aerocapture, aerobraking, entry and descent
TA10: Nano-Technology	Mars 2018, MSR: Sensors for chemical/bio assessment General: High-strength, lightweight customizable CTE materials; low-power radiation/fault tolerant electronics; high- sensitivity/selectivity sensors; nano-lasers; miniaturized magnetometer, spectrometer; single molecule/organism bio/chemical sensors, microfluidic lab on chip sensors; single-photon counting sensors; nano-thrusters for formation flying	Fab & Test: Optical instruments enhance/enable the development, fabrication, and characterization of nano technology

Technology Area	Other TA Technology required by SIOSS	SIOSS Technology required by Other TA
TA11: Modeling	General: Validated performance modeling for observatories, instruments, and spacecraft that integrate optical, structural, dynamic and thermal models MSR: Entry, descent, landing & launch systems integrated modeling & simulation Discovery 14, NF 4: Small body encounters General: Model-based systems engineering; integrated high-fidelity multi-scale multi-physics-based performance modeling	General: SIOSS technology to acquire data to validate multi-physics models for space and Earth weather needed for simulation fidelity
TA12: Materials & Structures	PUSH: Low-density, high stiffness, low-CTE materials; large, deployable or assembly, active or passive, ultra-stiff/stable, precision structures NF 4: Extreme environments (Venus, Titan) General: Mechanisms, hinges, docking, and interfaces; optical component materials	NDE: Perform NDE performance characterization for model-based certification and sustainment methods; dimensional and positional characterization IHM: Embedded sensors to characterize structure state, performance, and life assessment Optical: Materials and designs are required for low-scatter, high-strength damage-tolerant lightweight habitat windows
TA13: Ground/Launch Sys	PUSH: Ability to integrate very large science missions	IHM: Sensors for real-time in-situ measurements to reduce/eliminate over-purging practices; corrosion detection; anomalous conditions monitoring, toxic leaks, safety State Sensing: Sensors and vision systems to aid in flight hardware assembly; NDE structural integrity inspection; wireless or optical networks to access or transmit large quantities of safety data and information Operations: Advanced telemetry communication systems, high-data rate laser/optical com; visual and electronic range tracking Weather: SIOSS technology to acquire data to quantify and predict weather
TA14: Thermal Management	IXO: Sub-20K Cryo-Coolers MSR: Thermal Management of Mars Ascent Vehicle General: Low power cryocoolers (35K, 10-6K, and 2K); passive and active precision thermal control	Radiators: Optical emissivity coatings

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

All SIOSS technologies will benefit a range of national needs. Currently, NASA Earth Science missions are typically developed collaboratively with theother national agencies. Observatory and science-instrument technologies are commonly used by multiple communities, includingthe intelligence community, and commercial imaging companies. The primary difference between NASA and other potential beneficiaries is the technology's operating environment. For example, astrophysics and astronomical detectors/focal planes have similar low-noise sensitivity requirements but different operating environments, such as radiation hardness. A similar comparison can be made between planetary or heliophysics in-situ sensors and those used on the battlefield, in a hospital, at port and border checkpoints, or in a meat packing plant. X-ray mirror technology can be applied to commercial X-ray microscopes, X-ray lithography, or synchrotron optics. Space microwave, radar, or THz imaging systems can be applied to numerous government and industrial applications, for example, lidar/DIAL remote-sensing technology has applications ranging from cloud diagnostics to smoke stack pollution compliance.

ACRONYMS

ACE Aerosol/Cloud/Ecosystems
ADC Analog to Digital Converter
AMU Atomic Mass Unit
AO Autonomous Operation
APD Avalanche Diodes
APIO Advanced Planning and Integration Office
AR&D Autonomous Rendezvous and Docking
ASCENDS Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ASIC Application Specific Integrated Circuit
ATLAST Advanced Technology Large Aperture Space Telescope
APXS Alpha Particle X-Ray Spectrometer
AU Astronomical Units
BEP Beamed Energy Propulsion
CCD Charged Coupled Device
CheMin Chemical Mineral Instrument
CISR Climate Impacts of Space Radiation
COM Communications
CW Continuous Wave
DIAL Differential Absorption Lidar
DGC Dynamic Geospace Coupling
DHMR Dry Heat Microbial Reduction
EDL Entry, Descent and Landing
EJSM Europa-Jupiter System Mission
ELST Extremely Large Space Telescopes
EM Electromagnetic
EMS Environmental Monitoring and Safety
FAST Fast Auroral SnapshoT
FOV Field of View
FOXSI Focusing Optics X-ray Solar Imager
FPA Focal Plane Array
FWHM Full Width Half Maximum
GACM Global Atmospheric Composition Mission
GC-MS Gas Chromatography-Mass Spectroscopy
GenX Generation-X Vision
GEO Geosynchronous Orbit
GEO-CAPE Geostationary Coastal and Air Pollution Events
GPS Global Positioning Satellite
GRACE Gravity Recovery and Climate Experiment
GRIPS Gamma-Ray Imager/Polarimeter for Solar
HEDS Human Exploration Destination Systems
HERO High-Energy Replicated Optics
HiRISE High Resolution Imaging Science Experiment
HMaG Heliospheric Magnetics
HyspIRI Hyperspectral Infrared Imager
Hz Hertz
IHM Integrated Health Management
InGaAs Indium Gallium Arsenide
INMS Ion and Neutral Mass Spectrometer
INCA Ion-Neutral Coupling in the Atmosphere
ITP Inflation Technology Program
IXO International X-ray Observatory
JAXA Japanese Aerospace and Exploration Agency
LCAS Low-Cost Access to Space
LIBS Laser-Induced Breakdown Spectroscopy
LIMA Long-range laser Induced Mass Analysis
LISA Laser Interferometer Space Antenna
LIST Lidar Surface Topography
LROC Lunar Reconnaissance Orbiter Camera
MAHLI Mars Hand Lens Imager
MCP Microchannel Plate
Mdeg Millidegree
MECA Microscopy, Electrochemistry, and Conductivity Analyzer
MER Mars Exploration Rovers
MKIDS Microwave Kinetic Inductance Detectors
MSL Mars Science Lab
MSR Mars Sample Return
NDE Non-Destructive Evaluation
NEO Near Earth Object
NEP Noise Equivalent Power
NF New Frontiers
NIR Near Infrared
NRC National Research Council
NuSTAR Nuclear Spectroscopic Telescope Array
NW New Worlds
O Optical
ONSET Origins of Near Earth Plasma
OR&PE Object Recognition and Pose Estimation
PATH Precipitation and All Weather Temperature and Humidity
PNT Position, Navigation, and Timing
PRF Pulse Repetition Frequency
PSF Point Spread Function
PVP Photovoltaic Power
QE Quantum Efficiency
RAT Rock Abrasion Tool
RFI Radio Frequency Interference
ROIC Readout Integrated Circuit
SAIL Synthetic Aperture Imaging Lidar
SAR Synthetic Aperture Radar
SA/SPaH Sample Acquisition / Sample Processing and Handling
SCLP Snow and Cold Land Processes
SEM Scanning Electron Microscope
SEM Space Experiment Module
SEPAT Solar Energetic Particle Acceleration and Transport
SEU/SEL Single Event Upset/Single Event Latchup
SIOSS Science Instruments, Observatories, and Sensor Systems
SMD Science Mission Directorate

SPICA	Science Investigation Concept Studies
SSE	Solar System Exploration
STP	Solar Thermal Propulsion
SWOT	Surface Water and Ocean Topography
TABS	Technology Area Breakdown Structure
TEPC	Tissue Equivalent Proportional Radiation Counter
TES	Transition Edge Sensors
THEMIS	Time History of Events and Macroscale Interactions during Substorms
THz	TeraHertz
TID	Total Ionizing Dose
TIR	Total Internal Reflection
TPF-C	Terrestrial Planet Finder-Coronagraph
TPS	Thermal Protection System
T/R	Transmitter/Receiver
UAV	Unmanned Aerial Vehicle
UV	Ultraviolet
UVOIR	UV-Optical-near IR
VIS	Visible
WCL	Wet Chemistry Laboratory
WFE	Wall Plug Efficiency
WFOV	Wide Field of View
WFIRST	Wide-Field Infrared Survey Telescope
WFSC	Wavefront Sensing and Control
WINCS	Wind Ion-drift Neutral-ion Composition
WPT	Wireless Power Transmission
XMM	X-ray Multi-Mirror Mission
XRD	X-Ray Diffraction
XRF	X-ray Fluorescence

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